ENERGY INPUT-OUTPUT SIMULATION OF MIDWEST CROP PRODUCTION

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ABSTRACT

A simulator was developed to evaluate alternative agricultural practices for energy efficiency in Midwest crop production. It uses seven years of real weather data, including farmer observations of good working days which are used to simulate when field operations could be performed. Solar radiation, temperature, rainfall, and fertilizer inputs are used to calculate crop yields and harvest dates. The simulator uses inputs that describe the operation of a farm including the crop rotation, operations required for each crop, and the energy requirements of the operations. A priority system is included to determine the order of performing operations. Outputs summarizing crop production and energy use on the farm are produced by the simulator. Crop growth submodels are included for corn, winter wheat, soybeans, alfalfa hay, and hairy vetch, a legume which is plowed down for soil improvement.

INTRODUCTION

An Agricultural Energy Input-Output Simulator (AGNRG) has been developed at Purdue to evaluate alternative agricultural practices for energy efficiency in Midwest crop production. In this evaluation it was necessary to determine how alternative practices would affect the productivity of the farm as well as measure changes in energy inputs to the farm. Practices that reduce energy usage in one component of crop production might increase energy usage in another component, or significantly reduce crop yields and wipe out any gains in energy savings. The large number of interactive effects between cultural practices and weather that affect energy use and crop output make a systems approach a necessity.

The simulator was used to evaluate the technical feasibility of several energy-saving practices and to compare them with conventional practices. Its results were then used to evaluate the economic feasibility of the practices in the Purdue Farm Management Model B (8) or a related farm management linear programming model.

The present version of the simulator does not explicitly include animal production operations. However, animal manure can be used as a plant nutrient in the simulator and crop output is reported in a format that allows ready calculation of its value to livestock, that is digestible energy and protein.

One of the most important features of the model is that it does not operate under statistically average weather conditions. The simulator, which goes through the field operations of tilling, planting, etc. through harvesting, does this on the basis of actual weather data for a specific year. The crop yields are determined on the basis of the same weather data through the use of crop yield submodels. This actual weather feature is important because a practice that is optimal for an average year might completely fail in a poor weather year and be suboptimal over a period of several years. At the present time seven years of weather (1968-1974) are available to the simulator. Of particular importance in this weather data are observations of many farmers in west-central Indiana of which days were good working days. For each week, the average fraction of days being reported as good working days has been made available to the simulator. It is used to calculate when operations can be performed in each individual year. Thus, the actual cropping operations are subject to weather variation as they are in actual practice.

INPUTS

A description of the inputs and outputs will be helpful before the operation of the simulator is described. An outline of the inputs follows:

I. Farm Parameters
   A. Size of farm in acres
   B. Number of equal-sized field sections into which the farm will be divided
   C. Working hours per day

D. Working days per week
E. Crop rotation
F. Number of men
G. Machinery
    1. Name
    2. Number available
H. Alternate crops that may be used if it becomes too late to plant regular crops in the crop rotation

II. Energy Unit Used in the Simulator

III. Energy Sources
A. Name
B. Unit of source
C. Energy units per unit of energy source

IV. Nutrient sources
A. Name
B. Unit of source
C. Energy units per unit of nutrient source

V. Crops
A. Crop name
B. Nutrients required for crop
C. Operations required for crop
    1. Operation name
    2. Operation priority number (It must be unique for each operation and must be an integer between 1 and 50, inclusive. Lower numbered operations have higher priorities.)
    3. Rate in acres/hour (Non-positive rates indicate instantaneous operations.)
    4. Men required
    5. Earliest starting week
    6. Latest starting week
    7. Alternate operation and crop year used if latest starting week is passed and operation has not started
    8. Whether or not operation requires tillage
    9. Moisture content (for starting harvest and finishing drying only)
    10. Machinery required
        a. Name
        b. Number
    11. Energy and nutrient sources required
        a. Name
        b. Amount
D. Next operation and crop year after crop is finished (defaults to first operation for next crop in crop rotation if not specified)
E. Operational branches (groups of operations not normally performed which can be used if normal operation cannot be started by the latest starting week or to provide alternate tillage strategies to follow different crops)
    1. The type of the first operation in the branch (yield multiplier, pre-planting, planting, post-planting, harvesting, drying, or post-harvesting)
    2. Operations in branch (requires the same information as "Operations required for crop")
    3. The next operation to be performed after operational branch is finished

VI. Number of Operations Normally Performed in the Spring That Can Be Performed the Previous Fall

VII. Initial Conditions of the Field Sections
A. Crop year in the crop rotation
B. Fertility
C. First operation
D. Planting date if a crop is currently growing

VIII. Weather Dependent Data
A. Weekly good working day data
B. ECG data for corn growth (6)
C. Maturity date data for corn
D. Thompson's model yield data for wheat and soybeans (16,17)
E. Dates of first killing frosts

OUTPUTS

An outline of the outputs of the simulator for each year follows:

I. Year

II. Crops
A. Crop name
B. Acres planted
C. Total yield
D. For each period (pre-planting, planting, post-planting, harvesting, and post-harvesting)
    1. Amount of each energy and nutrient source used in the period
    2. Total energy used in the period
    3. Starting week of the period
    4. Finishing week of the period
E. Total amount of each energy and nutrient source used for the year
F. Total energy used for the year

III. Sum of Each Energy and Nutrient Source Used in All Crops for the Year
IV. Sum of Total Energy Used in All Crops for the Year

When all years have been simulated, a summary of the averages of the above quantities is included in the output. In addition, the following averages are included at this point:

I. Digestible Energy in Crops Grown
II. Digestible Protein in Crops Grown
III. Ratio of Digestible Energy to Total Energy Used
IV. Ratio of Digestible Protein to Total Energy Used

OPERATION OF THE MAIN SIMULATOR

After all of the inputs have been read by the simulator, the first operation in each section is placed into a job queue in order from the lowest operation number (highest priority) to the highest. In case of a tie, the operation from the lowest numbered section is first. Then the maximum number of working hours per week is computed by multiplying the working hours per day by the working days per week. The number of each machine type and the number of men are then multiplied by this quantity to give the maximum machine-hours of each machine type and man-hours, respectively, per week.

At the beginning of each week, the maximum machine-hours of each machine type and man-hours per week are multiplied by the fraction of good working days reported for that week to give the available machine-hours of each machine type and man-hours, respectively, for that week. The simulator then tries to perform each operation in the job queue starting with the highest priority operation. If adequate resources (manpower and machinery) are available, the operation is completed. Then available resources are recalculated, amounts of energy and nutrient sources used are computed, and the next operation to be performed in this section is placed into the job queue. However, if adequate resources are not available, enough of the operation is completed to exhaust the most limiting resource, and available resources are recalculated. After an operation has been attempted, its alternate operation is placed into the job queue if this is the last week the operation can be started and it has not done so. No operation is worked on before its start date nor is any operation requiring tillage worked on after week 35 (ending Dec. 5) because the ground is assumed to be frozen or otherwise untillable after this date.

Whenever a new operation is to be placed into the job queue and it is to be performed in the following year (including spring operations that can be performed in the fall), 50 is added to its priority number as an indicator. If the last week the operation can be started has passed, its alternate operation is placed into the job queue instead. If the operation has a higher priority than the operation from this section which it is to replace, the simulator will immediately try to perform it before placing it into the job queue. New operations are placed into the job queue behind all operations with equal or lower operation priority numbers and ahead of all operations with higher operation priority numbers.

The operation priority numbers indicate the order that competing operations in different sections will be attempted, not the order which a series of operations will be attempted in an individual section. Following is a simplified illustration with corn being grown in one section and wheat in another.

CORN FULL		WHEAT	
PLOWING	1	DISC1	19
DISC1	7	DISC2	18
APPLY NH3	6	PLANT	17
DISC2	5	FERTILIZE	2
PLANT	3	HARVEST	9
CULTIVATE	10	DRYING	8
HARVEST	13		
DRYING	12		

Each crop begins with its first operation. For corn that would be PLOWING, 1. After completing that operation that crop's next operation comes up, eg. DISC1, 7. Before attempting operation number 7, the simulator will check the other sections for a priority number lower than 7. Since wheat was planted in the fall in the other section, it would have completed operation number 17 (PLANTING) and have operation 2 (FERTILIZE, assuming it is the first spring operation) up next. Since 2 is lower than 7, wheat would be fertilized, bringing operation 9 (HARVEST) up next. However, 7 is lower than 9, so the first corn discing would be done next. This continues in like manner until completion. However, if in the first week, there were not enough plowing-hours available to complete plowing for corn, the simulator would try to complete wheat fertilization. Then next week, it would try to finish plowing for corn.

After all operations have been attempted, the simulator moves on to the next week and repeats the above procedure. After all 40 weeks have completed (The first week begins Mar. 29 and the last week ends Jan. 2.), the simulator computes the amounts of energy and nutrient sources used in unfinished operations, initializes the job queue for the next year, and produces a summary for the year of the crop acreages planted, total crop yields, the amount of each energy and nutrient source consumed and the time interval required by each operation type for each crop. The simulator then moves on to the first week of the next year. After all years have been simulated, a summary of the averages of the values in the yearly summaries plus average digestible energy and protein outputs and output/input ratios of these with total energy input are produced and the simulation is terminated.

Reference (13) contains more detailed documentation of AGNRC including a listing of the computer program with a description of all variables, a conceptual flow chart, and a detailed description of the data input format.

CROP SUBMODELS

The simulator contains a crop growth and harvesting submodel for each different crop which computes the moisture content of the crop, determines if harvesting can begin, determines the crop yield after harvesting losses, and computes the fertility levels after harvesting given the current week, year, and fertility levels before harvesting. Currently the simulator contains submodels for the three basic cash grain crops in the Midwest: corn, winter wheat, and soybeans. Short-, mid-, and full-season varieties of corn have all been considered. Submodels are also available for alfalfa hay and hairy vetch which is plowed down for soil improvement, neither being based on weather data at the present time.

All of the crop submodels have been formulated so that yields are determined by entering a yield table for the particular year and crop and/or performing some simple calculations once for each crop (once for each cutting for alfalfa) in each section. No yield calculations are performed on a daily or weekly basis in the simulator. All calculations that would normally be performed on a daily basis have been moved outside the model and their results summarized in yield tables. Although this reduces the flexibility of the yield submodels by reducing the complexity of interactions that can be considered, it results in very fast run times for the model.

The following set of symbols will be used in describing the submodels:

- ECG, energy-crop growth factor for corn (6)
- FW, number of weeks from premature first killing frost to the maturity date
- HM, wet basis moisture content of the crop at harvest, percent
- N_T, the total available nitrogen in lb/acre (nitrogen applied plus the carry-over nitrogen from the previous crop)
- P, planting week (Week 1 starts Mar. 29.)
- TY, yield predicted by Thompson's models (15,16) for Indiana for the given crop with 1974 technology (bu/acre)
- Y, yield of crop after losses (bu/acre)
- YB, base yield before losses (bu/acre)
- YF, yield multiplier for early frost (0-1.0)
- YH, yield multiplier for late harvest (0-1.0)
- YM, yield multiplier for high moisture (0-1.0)
- YP, yield multiplier for late planting (0-1.0)

For the grain crops, the yield is determined by the equation:

$$Y = YB * YF * YH * YM * YP$$

where some of these multipliers may be unity. In addition, the yield of any crop can be modified by including a yield multiplier operation which will multiply the yield by a constant. For example a 0.85 multiplier was used in an operational branch that was only executed when corn cultivation was missed. In the following sections, it will be assumed that no nutrients are limiting except nitrogen in all the crops.

CORN SUBMODEL

This is the most complex of the yield submodels, being closer to a true plant growth model than a weather-yield regression model like those utilized for wheat and soybeans. It uses the ECG factor developed by Dale (6) which approximates the amount of energy available for photosynthesis. The ECG factor is computed by accumulating daily ECG (DECG) over a period from six weeks before silking to six weeks after silking where:

$$DECG = \frac{SR}{600} \left(1 - e^{-0.79\ LAI} \right) \frac{ET}{PET}$$

where SR is the solar radiation in langleys, LAI is the leaf area index, ET is the actual evapotranspiration, and PET is the potential evapotranspiration. The ratio between the evapotranspiration terms is calculated daily by SIMBAL, a moisture balance simulator. Leaf area index is estimated as a function of phenological day and variety. The simulator's requirement for daily solar radiation data limited its application to a seven year period (1968-1974) for west-central Indiana when it was developed. Recently, however, the solar radiation data for this area has been extended to more than 20 years by estimating it with regression on Indianapolis data but the necessary calculations have not been made to incorporate this data into the simulator.

Dale's model was adjusted to use total nitrogen instead of applied nitrogen and to taper off yield increases at higher nitrogen levels producing the following equations:

IF $N_T < (6.528\ ECG - 60.24)$ then,

$$YB = 8.266 - 0.1506\ N_T - 0.00125\ N_T^2 + 0.5088\ ECG + 0.01632\ N_T * ECG$$

otherwise,

$$YB = 12.802072 - 0.4743168\ ECG + 0.05326848\ ECG^2$$

These equations are compared to observed data with an ECG factor of 55 (average conditions for early-planted, full-season corn) in Figure 1. Figure 2 shows the yield as a function of total available nitrogen and the ECG factor before losses.

The early frost and late harvesting losses are based on values used in Purdue's Corn Harvesting Simulator (12):

$$YF = \begin{cases} 1 - 0.0098\ FW & ;\ \text{if } FW \le 6 \\ 0.6 & ;\ \text{if } FW > 6 \end{cases}$$

$$YM = 1 - 0.01\ WM$$

The high moisture losses are based on data presented by Johnson and Lamp (9):

$$YM = \begin{cases} 1 & ;\ \text{if } HM \le 23 \\ 1.115 - 0.005\ HM & ;\ \text{if } HM > 23 \end{cases}$$

The late planting factor is set to unity for corn because late planting losses are accounted for by the ECG factor. The maturity date for corn is assumed to be 56 days past silking and silking is assumed to be 1300, 1400, and 1500 growing degree-days (50°F base) past the planting date for short-, mid-, and full-season varieties, respectively.

At maturity, corn is assumed to be 33 percent moisture (4) but it is increased 2.1 percent for each week the corn was frosted prematurely up to a maximum of 40 percent (12). The following dry-down rates are being used before Nov. 1 (Dry-down is assumed to stop Nov. 1.):

Above 29%	; 3.5%/week (0.5%/day)
29% - 25%	; 2.33%/week (0.33%/day)
25% - 17.5%	; 1.4%/week (0.2%/day)
17.5%	; 0

These rates are slightly lower than those reported by Johnson and Lamp (9) for Ohio and considerably lower than those reported by Miles (11) for Indiana and Kiesselbach (10) in Nebraska but higher than those reported by Bruns (4) in Indiana. At a later date Bruns's dry-down model which requires daily values for net radiation, mean wind speed, mean temperature, and mean dew-point might be incorporated into the model.

Nitrogen carried over to the next crop is assumed to be one-third of N_T up to a maximum of 75 lb/acre (1).

SOYBEAN SUBMODEL

Since Thompson's model (17) was based on state yield averages which include good and poor land, adequate and inadequate fertilization, early and late plantings, and high and low harvesting losses, it gives relatively low yields. Model B (8) uses average yields for early planting and early harvesting of 48 bu/acre for soybeans and 60 bu/acre for wheat compared to 30 bu/acre and 40 bu/acre, respectively, used by Thompson's model. Therefore the following equation was used to compute the soybean base yield:

$$YB = 1.6\ TY$$

Thompson's model with Indiana coefficients was used with X1, the technology variable, always set at 44 to indicate current technology (1974), thus:

$$TY = 15.81 + 0.3236\ X1 + 0.0401\ X2 - 0.0015\ X2^2 + 0.0743\ X3 - 0.0095\ X3^2 + 0.0944\ X4 + 0.0606\ X4^2 + 1.0478\ X5 - 0.0968\ X5^2 - 0.0049\ X6 + 0.0839\ X6^2 + 0.9700\ X7 - 0.4170\ X7^2 - 0.1474\ X8 - 0.0930\ X8^2$$

where

X1 = (Year - 1930)
X2 = actual total precipitation from Sept. through May minus normal precipitation for the same period, inches
X3 = actual June precipitation minus normal June precipitation, inches
X4 = actual June mean temperature minus normal June mean temperature, degrees F
X5 = actual July precipitation minus normal July precipitation, inches
X6 = actual July mean temperature minus normal July mean temperature, degrees F
X7 = actual Aug. precipitation minus normal Aug. precipitation, inches

X8 = actual Aug. mean temperature minus normal Aug. mean temperature, degrees F

The following maturity schedule is used for soybeans (15,8):

Planting Dates	Maturity Date
May 17 and earlier	Sep. 27
May 24, 31, and June 7	Oct. 4
June 14, 21, 28	Oct. 11
July 5, 12	Oct. 18

The yield multiplier for late harvesting is based on data from Byg (5):

$$YH = 1 - 0.011\ WM$$

For late planting, the following equation based on data from Swearingin (15) is being used (Week 8 starts May 17.):

$$YP = \begin{cases} 1 & ;\ \text{if } P \leq 8 \\ 0.5896 + 0.1099\ P - 0.00735\ P & ;\ \text{if } P > 8 \end{cases}$$

Since soybean dry-down rates are very fast and highly weather dependent and soybeans rewet very easily, it was decided not to use a dry-down model but to assume moisture content is a constant 13 percent after maturity. Therefore the high moisture yield multiplier was unity. The early frost multiplier was also set to unity because frost never occurred early enough to reduce yields in the seven year period. Carry-over nitrogen to the next crop from soybeans is assumed to be 75 lb/acre (2).

WHEAT SUBMODEL

Thompson's wheat model (16) with Indiana coefficients was used, again using 1974 technology.

$$TY = 13.488 + 0.217\ X1 + 0.933\ X2$$
$$- 0.008\ X2^2 - 0.229\ X3 - 0.141\ X4$$
$$+ 0.015\ X5 - 0.022\ X5^2 - 0.317\ X6$$
$$- 0.072\ X6^2 - 0.397\ X7 + 0.013\ X7^2$$
$$- 0.730\ X8 - 1.21\ X9$$

where

X1 = (Year - 1919) if Year < 1945, 26 otherwise
X2 = 0 if Year < 1945, (Year - 1945) otherwise
X3 = actual total precipitation from Aug. through Mar. minus total normal precipitation for the same period, inches
X4 = actual Apr. precipitation minus normal Apr. precipitation, inches
X5 = actual Apr. mean temperature minus normal Apr. mean temperature, degrees F
X6 = actual May precipitation minus normal May precipitation, inches
X7 = actual May mean temperature minus normal May mean temperature, degrees F
X8 = actual June precipitation minus normal June precipitation, inches
X9 = actual June mean temperature minus normal June mean temperature, degrees F

Data from Swearingin (15) was used to produce the following equations:

If $N_T < 200$ then,

$$YB = (0.3 + 0.012\ N_T - 0.00003\ N_T^2)\ TY$$

otherwise,

$$YB = 1.5\ TY$$

As with soybeans, the early frost and high moisture multipliers are both unity. The following equation based on data from Richey (14) is being used for late harvesting:

$$YH = 1 - 0.02\ WM$$

Data from Swearingin (15) was used to adjust for late planting as follows:

$$YB = \begin{cases} 1 & ;\ P \leq 28\ \text{(Oct.4)} \\ 1.84 - 0.03\ P & ;\ P > 28 \end{cases}$$

Wheat is assumed to be mature at 22 percent moisture on June 28 and dried down to 14 percent on July 5 and after (14,3). Nitrogen carry-over to the next crop is assumed to be one-third of the total nitrogen up to a maximum of 75 lb/acre (same as corn as no data was found).

ALFALFA SUBMODEL

Currently a very simple yield model is being used based on harvesting week:

$$Y = \begin{cases} 2.3 & ;\ \text{if } 9 \leq HW < 15\ \text{(normal 1st cutting)} \\ 1.7 & ;\ \text{if } 15 \leq HW < 21\ \text{(normal 2nd cutting)} \\ 1.3 & ;\ \text{if } 21 \leq HW \leq 24\ \text{(normal 3rd cutting)} \\ 0.7 & ;\ \text{if } HW \geq 30\ \text{(normal 4th cutting)} \end{cases}$$

where Y is the yield in tons/acre and HW is the harvesting week. The nitrogen carry-over is assumed to be 150 lb/acre.

VETCH MODEL

Since the hairy vetch is plowed down, no yield model is used and the yield shown in the output is the total nitrogen added to the soil. The following equation is being used for the amount of nitrogen added in lb/acre (N_A) in addition to nitrogen carried over from the previous crop:

$$N_A = \begin{cases} 10\ W + 15 & ;\ \text{if } 2 \leq W \leq 8 \\ 100 & ;\ \text{if } W > 8 \end{cases}$$

where W is the week the vetch is plowed down (W = 1 starts Mar. 29).

RESULTS

The major results of early runs of AGNRG with economic analysis provided by the Purdue Farm Management Model B are summarized below:

1. Digestible energy outputs per unit of energy input for Corn Belt crops on non-irrigated, productive soils range from 6 for corn and wheat to 10 for alfalfa and 12 for soybeans. Inputs not included were energy for machinery manufacture, seed production, and labor, calculated to be less than 10% of the total inputs.
2. A winter legume cover crop between soybeans and corn in the rotation can improve energy efficiency by 20% and can aid in soil and water conservation, but at current prices, establishing the cover is more expensive than the nitrogen fertilizer (which accounts for about 50% of the total energy input to conventional corn production) it saves and corn yields are reduced by delayed corn planting. If the vetch is killed by a defoliant instead of plowing it down, the corn yields are not reduced, but the extra nitrogen and herbicide needed are more expensive at current prices than the corn saved.
3. A rotation including one-third alfalfa can improve energy efficiency about 20% over a corn-soybeans rotation and be just as profitable at current prices with good alfalfa yields.
4. Delaying harvest to reduce energy for drying corn is not profitable at current prices, but developments in crop residue gasification, heat pumps, and solar and low temperature drying could greatly reduce the fuel requirements of drying (about 25% of the total energy input to conventional corn production).
5. Production of double-crop wheat and soybeans is 25% more energy efficient than wheat alone, but less energy efficient than soybeans alone and less profitable than corn or corn-soybeans rotations at current prices.

Doering (7) gives a detailed description of the project for which this simulator was developed. He also presents more detailed results of this study including results produced by the simulator.

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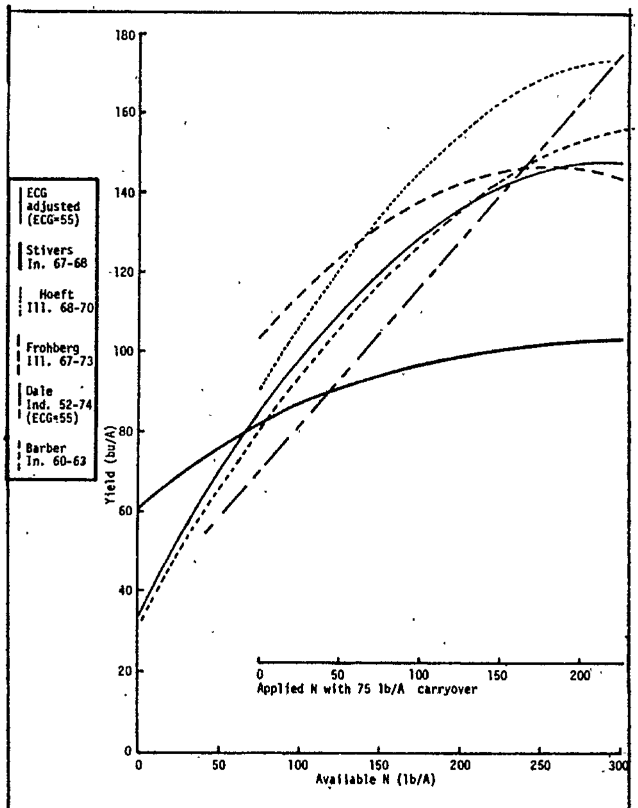

Figure 1. Adjusted energy crop growth model (ECG) compared to other data on corn yield response to nitrogen

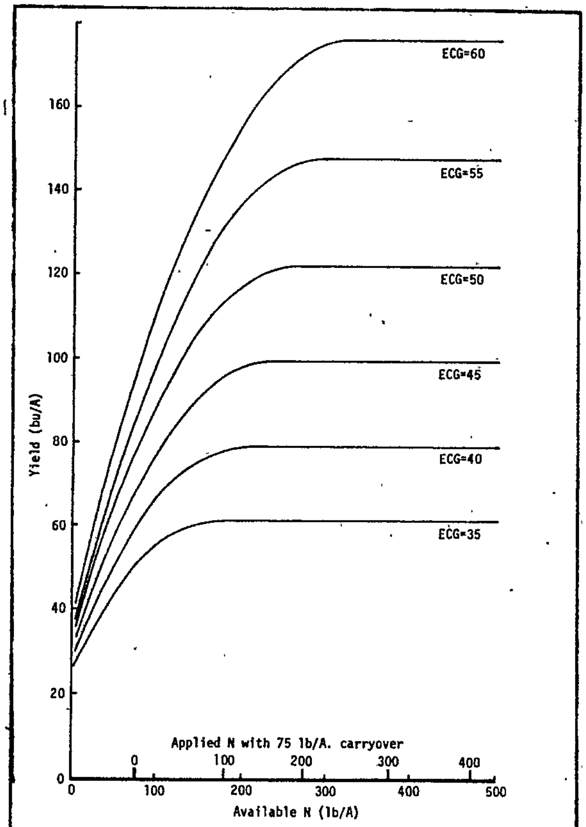

Figure 2. Corn yield response to nitrogen and weather in adjusted ECG model