CropFLEX-A Vadose Zone Quality and Farm Sustainability Decision Support Tool for Managing Irrigation and Fertilizer

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Introduction

Groundwater is an important source of drinking water for individuals living on many farms and in small rural communities because of its availability and general good quality. Water quality professionals have become keenly aware of the impact that agricultural practices can have on groundwater quality. This contamination can be caused by the use of fertilizers and pesticides. Among the concerns for nonpoint sources of pollution, groundwater contamination by nitrate originating from inefficient irrigation and fertility management practices has become an important issue.

Deep percolation of water through the soil profile is a main cause of nitrate contamination. When excessive water percolates through the soil profile the very soluable nitrate can be carried below the rooting depth of the crop. The nitrate will continue to move downward within the vadose zone and if not denitrified it will ultimately end up in the groundwater.

The first level of response to this issue advocates voluntary prevention. This response promotes the development and adoption of Best Management Practices (BMP's) designed to manage and prevent water quality degradation. These BMP's are conventions known to decrease the potential for groundwater contamination by increasing the level of on-farm crop management.

Considering the inherent dependency of nitrate transport processes on irrigation management the level of BMP's become quite comprehensive in an irrigated crop management system. Best Management Practices related to irrigation include soil water estimation procedures to avoid over application of water, and recognition that the management allowed deficit may vary with crop stage growth. Examples of nitrogen management BMP's would include deep soil sampling, crediting non-fertilizer sources of nitrogen, considering a realistic and obtainable yield goal, splitting fertilizer applications, and selecting appropriate sources of nitrogen. Decision Support Tools are emerging as a way to speed the adoption of management techniques.

The definition of a Decision Support Tool as dicussed here, is an integrated computer software package designed to provide multifaceted decision support to aid the management of a crop production system. This is achieved by easily illustrating and describing the consequences of user made decisions. A user can employ the decision support tool without understanding the complex physical processes that the model simulates. Thus, the end user gains the benefits of domain expertise without the requirement of understanding the details of the phenomena.

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CropFLEX has been developed as one of the first attempts to combine irrigation scheduling with fertilizer management into a single decision support tool with the following key components:

- An irrigation scheduler to recommend the amount and timing of irrigation applications.
- A fertility scheduler to recommend the amount and fertilizer application timing of available fertilizer formulations and materials.
- A simple leaching model to assess the amount of nitrate that will leach under a proposed irrigation and fertility management scheme.

Decision Support Tool Design

CropFLEX was written in ANSI C using Borland C+ Version 3.0 compiler, linker, and debugger. The model has a complete screen based user interface windowing environment employing the C-Scape Interface Management System.

Farmer acceptance of this decision support tool will be largely based upon 1) the ease which it can be used, and 2) the quality of the management advice it provides. The model has been designed with the the goal of providing a fully interactive user interface which is intuitive as possible, that is, the user should have to rely on the user manual as little as possible.

Irrigation Scheduler. The irrigation scheduler uses a traditional soil water mass balance approach and the concept of a critical soil water depletion level to trigger irrigation recommendations. It operates in a real-time mode using daily climatic data to estimate the reference and actual crop evapotranspiration (ET). The model is designed to forecast irrigation requirements one day in advance. The user has a choice of calculating the reference ET using a Penman, Jensen-Haise, or modified Hargreaves method. In addition the reference ET can also be directly input if it is calculated or determined from a different source.

The user can select the choice of units with which the model works and can calibrate the reference ET methods if site specific calibration information exists. The stage of crop development, daily crop coefficient, and irrigation decision calculations can be estimated using either season days or growing degree days. The irrigation scheduler has been developed to be used with any crop for which crop coefficients exist.

Fertility Scheduler. The fertility scheduler provides preseason nutrient recommendations for three nutrients: nitrogen, phosphorus, and potassium. The phosphorus and potassium recommendation are based upon availability indicies.

The nitrogen recommendation is based upon three independent decisions. The three nitrogen recommendation decisions are based upon the traditionals soil test method, an inorganic nitrogen mass balance, and a crop-use efficiency method. A conflict resolution scheme is used to resolve any discrepancies that occur between the three decisions and obtain a single recommendation.

The model then schedules the nutrient recommendations for specific fertilizer materials in applications across the season. Currently, the fertility scheduler is limited to corn and onion.

Leaching Model. The leaching model utilizes the management information generated by the irrigation scheduler and fertility scheduler to evaluate the potential impacts of the management strategy on nitrate leaching. The leaching model calculates the amount of water deep percolating and the nitrate available for leaching during the season. An additional feature of the model is to estimate the yield reduction that would be obtained if the amount of nitrogen fertilizer applied was reduced to minimize the nitrate leaching.

Decision Support Tool Philosophy and Calculations

Information is organized and stratified by year, location, farm, and field. The year represents the current year of interest. Scheduling with CropFLEX can be performed for any year from 1950 to 2049 with internal automatic compensation for leap years. The current version (2.05) allows a daily scheduling calendar from March 1 to September 30.

A location refers to any geographical area which can be represented with one set of meterological data. Consequently, the model assumes that the reference ET will be equal on each farm within a location. The size of the geographical area associated with a location must be determined with the user's discretion. It is recognized that the area size should be sufficiently small that the weather on each farm designated within the location can be accurately represented by a single meteorlogical station or data collection point. All location specific information and daily meteorlogical information is stored within a location file.

A farm is a collection of fields associated with a location. The farm has no data characteristics of its own; rather, it provides an easy way to organize and designate the fields that belong to a particular farmer.

A field is the scheduling entity within a farm. Soil, crop, irrigation system, and field management information is attached to the field. Soils information includes textural grade, field capacity, permanent wilting point, and available water holding capacity.

Crop information includes crop name, variety, planting depth, maximum rooting depth, growing degree day model thresholds, and regression coefficients for calculating basal crop ET coefficients. The internal nitrogen requirement, nitrogen uptake efficiencies, phosphorus and potassium availability indices are also included as a part of the crop information.

The crop information specific to each growth stage specifies the duration of growth and defines the maximum allowable depletion during each growth stage. Management flags are also included that asssociates certain management events that the model recognizes with certain growth stages. These include planting, emergence, full cover, irrigation termination, and harvest.

Irrigation system information consists of data that identifies and characterizes the field's irrigation system including system type and application efficiency.

Field management information consists of farmer controlled management plus initial soil water status. Planting date, harvest date, initial starting date, and initial soil water content are described by the user.

The meteorological information for a field is inherited from the associated location. When a field or location is created, it automatically inherits the information from the same field or location of the previous year.

Irrigation Scheduler. The irrigation scheduler uses a two-layered soil water mass balance to calculate the soil water content within the root zone using a daily time step. The size of the top layer corrresponds to the current rooting depth of the crop. The user has a choice between a linear and curvilinear function. The linear function assumes that the crop rooting depth grows linearly from a planting depth to a maximum depth at full cover. The curvilinear function of Borg and Williams (1986) is used to describe a crop's rooting depth pattern based upon the maximum root depth and time to reach maturity.

As roots grow the size of the top layer increases and the size of the bottom layer decreases. Inputs to the top layer include effective precipitation and irrigation; output from the top layer results from actual crop ET. When the soil water content within the top layer exceeds field capacity, the excess percolates into the second layer.

The user must input the effective precipitation directly with the current version. The effective irrigation is calculated from the total amount applied and the application efficiency.

The second layer of the mass balance is used to determine the amount of soil water percolating below the maximum root depth with input of the percolating water from the upper layer. As in the case of the upper layer deep percolation occurs when the soil water content is above field capacity. The water balance instantaneously drains the excess water after twenty-four hours (one time-step).

Many different capabilities have been incorporated into the model to provide as much flexibility as possible. The user can select the reference ET method of choice. The selection of the method should be made based upom the available data and the user's preference. Currently available ET estimation methods include the 1982 Kimberly Penman combination method, the Jensen-Haise radiation method and the modified Hargreaves radiation method.

As applied in CropFLEX, the variable wind function as originally applied to the 1982 Kimberly Penman is not used; rather a default wind function is used that remains constant throughout the season. The Jensen-Haise radiation method (1963) is implemented as originally described. Based on the original Hargreaves radiation method (1975), it was modified to estimate the potential ET of an alfalfa reference crop rather than a grass reference crop (Hargreaves, 1992). A wind correction factor was also added to calibrate the method to Colorado conditions (Salazar, 1992).

Fertility Scheduler. The fertility scheduler provides preseason fertility scheduling advice for irrigated crops. The model makes fertility recommendations for three nutrients: nitrogen, phophorus, and potassium. The model then schedules the fertilizer material for applications throughout the season.

The phosphorus and potassium recommendations are based upon availability indices determined from soil tests. The Colorado availability indicies are currently a part of the crops database in CropFLEX (Follett *et al.*, 1991). An additional feature in making phosphorus recommendations is the flexibility of assessing phosphorus availability from three commonly accepted extraction methods, the Bray test, Olsen test, or the AB-DTPA test. The two latter tests are appropriate for alkaline soils where calcium phosphate is the dominant compound. The Bray should be used in acid soils where iron and aluminum phosphates are the dominant phosphorus compounds.

The nitrogen recommendation is based upon three methods with independent nitrogen decisions determined with each method. First, the nitrogen needed is determined using a traditional soil test method based upon yield goal. For corn the "Nebraska algorithm" (Hergert, *et al.*, 1995; Mortvedt, *et al.*, 1994) is used. For all other crops the Colorado State University algorithms are used (Follett *et al.*, 1991). Nitrogen credits are given for manure (5 lbs N/ton, as is), legumes, and nitrogen in the irrigation water, if known.

A second decision regarding the nitrogen amount needed is determed using an inorganic nitrogen mass balance. This approach is very similar to the screening analysis procedure in the NLEAP model (Pierce, *et al.*, 1991). The mass balance considers the following as inputs and outputs to the residual soil nitrogen pool:

Nitrogen Inputs:

Fertilizer
Organic matter mineralization
Crop residue mineralization
Symbiotic fixation (legume)
Manure mineralization
Irrigation water

Nitrogen Outputs:

Plant requirement
Denitrification
Leaching

The residual soil nitrogen pool represents the amount of nitrogen within the soil at the beginning of the season. The assumption is that most of the ammonium present during the previous fall, winter, and spring has nitrified. Consequently, the residual inorganic nitrogen pool is predominately in the nitrate form.

Another feature of the inorganic mass balance method assumes that some of the residual nitrate is not plant available due to the phenomenon of clay entrapment and that soil testing procedures are more effective than roots at removing nitrate from the soil. This unavailable residual nitrate is estimated from the soil clay content (Schepers and Mosier, 1991).

The seasonal denitrification is determined using the equation of Meisinger and Randall (1991). The rate constant is a function of the soil organic matter, pH, and the drainage class associated with a soil textural grade. If the soil pH is less than 5, denitrification is set to zero. CropFLEX also considers the influence of tillage practices and compacted layers in estimating denitrification. If a no-till practice is in place, one drainage class wetter is used. If the field is tile drained, the drainage class is adjusted to one class drier, while if the field contains a compacted layer, one wetter class is used.

The third method used to determine the needed nitrogen is a plant uptake efficiency method, hereby called the "CSU Efficiency Method." This method is identical to the inorganic nitrogen mass balance in terms of inputs and outputs. However, rather than trying to quantify the system losses explicitly, the method uses plant uptake efficiencies to quantify the losses implicitly. First estimates of the efficiencies can be found in CropFLEX. The quantification of the efficiency factors are currently being investigated (Soltanpour, 1993).

Organic matter mineralization, irrigation water nitrate, and determination of the residual soil nitrate pool are the same as in the inorganic mass balance method. Nitrogen credits for legumes and manure is calculated as in the soil test method.

Conflict Resolution. The fertility scheduler was developed to handle uncertainty. Once all three nitrogen methods reach their respective decision in terms of the amount of nitrogen required, a conflict resolution strategy is implemented to extract from them a single nitrogen recommendation which represents our best estimate of the actual amount needed.

This is accomplished by reevaluating all of the assumptions of each of the three methods. In the case of the traditional soil test method there are 25 assumptions, while there are 49 assumptions associated with the inorganic mass balance method, and 26 assumptions associated with the CSU efficiency method. For each assumption that may be inaccurate, a disbelief factor is assigned.

The disbelief factor is composed of a measure of disbelief and a measure of importance. The measure of disbelief is subjective which represents the level of supported knowledge for the assumption. The measure of importance represents how much effect the assumption has on the entire decision. The certainty factor is then assigned to each method based on the disbelief factors of the assumptions. The certainty factor is initially set at 100 percent for a method and then is adjusted downward by subtracting the sum of the disbelief factors associated with the method assumptions.

Scheduling Fertilizer Materials. After the nutrient recommendations have been made, the model schedules the fertilizer applications. The user makes a decision as to when fertilizers will be applied. At present CropFLEX allows the user a choice of sixteen application timings. The model recognizes preplant, starter, post-emergence, and fertigation application timing. The user may chose any combination of these four timings. The model extracts the fraction of total nutrient to schedule at each timing stage with values that were determined in conjunction with local domain experts. Once the model knows which nutrients to schedule for each timing stage, it queries the user to find out which fertilizer material will be applied.

If the user is planning to use a custom blend that is unknown to the system, the user may tell the model the blend name, nutrient content, allowable application phases, and maximum application amounts. If, on the other hand, the user wishes to use a source material fertilizer, the model will pop up a list of common fertilizer materials and formulations recognized by the the model. The fertilizer materials known to the model are contained in three fertilizer library files. Included in these fertilizer library files, are data describing the nutrient composition, allowable application phase (solid, liquid, pressurized liquids-gas) and the volatility class.

After choosing the fertilizer source and fertilizer phase, the user selects the fertilizer application method. The method quantifies how deeply the fertilizer is incorporated into the soil, which in turns affects the amount of fertilizer that will volatilize during application. Coupled with knowledge about soil pH and the cation exchange capacity, and expected rain or irrigation following application the model determines the amount of fertilizer that was lost during the application. The user can then make a decision on whether to compensate for the volatilization losses with additional fertilizer.

Leaching Model. The model takes a proposed fertility schedule and evaluates the potential leaching during the crop season. The model also determines the yield reduction which would be sustained if the amount of fertilizer was reduced to minimize leaching.

CropFLEX uses the same screening approach as is applied in NLEAP where a series of indicators are determined. These include the Leaching Index (LI), the amount of of nitrate available for leaching (NAL) and the nitrate leached (NL). Since the current season for which the analysis is being performed has not yet begum, the leaching model uses the irrigation schedule from the previous season.

As an evaluation of irrigation management, CropFLEX summarizes the amount of deep percolation, total water applied over the previous season, number of irrigation applications, water applied per irrigation and the average interval between irrigations. These indicators are determined to provide the user with general information in addition to the nitrogen leaching indicators to judge the performance of the management system.

The leaching portion of CropFLEX only operates from planting to harvest. As a consequence, the model is unable to recognize the leaching which may occur during the late fall, winter, or early spring. In some geographic regions this winter leaching may be significant, in which case the model recommendations may be misleading.

CropFLEX uses a modified quadratic/plateau model to determine the yield reduction which would be obtined if the nitrogen fertilizer were reduced to minimize the amount of nitrate leaching. This approach is described in detail elsewhere (Bock, *et al.*, 1991, Bock and Sikora, 1990, Bock, 1984, Meisinger, 1984, and Capurro and Voss, 1981). The reader is referred to these references for additional detail.

Summary

CropFLEX represents a decision support tool as an emerging technology in an attempt to combine fertility and irrigation management into an integrated crop management system. The model has the flexibility required to represent many different farm management scenarios. Examples of the flexibility include the irrigation scheduler's ability to work from user's choice of units and display soil water output in different expressions. A strength of the fertility scheduler includes the ability to determine the amount of fertilizer material that should be applied while consideration is given to fertilizer volatility and the user's preference of fertilizer materials.

One of the major weaknesses is that the irrigation scheduler is memory intensive and does not have the ability to use high memory. An inherent problem is the that other memory resident programs consume part of the 640K conventional memory, and as a consequence, the irrigation scheduler is limited to the number of days considered in the season. The inability of the current version to reset the soil water content midseason is a weakness.

The demand for decision support tools such as CropFLEX will likely intensify because they can assist in reducing over applications of water and fertilizers, and in turn, increase the sustainability and economic viability of the farm.

References

Bock, B.R. 1984. Efficient use of nitrogen in cropping systems. *In:* R.D. Hauk (ed), Nitrogen in Crop Production. ASA/CSSA/SSSA, Madison, WI p. 273-306.

Bock, B.R. and F.J. Sikora. 1990. Modified-quadratic/plateau model for describing plant response to fertilizer. Soil Sci. Soc. Am. J. 54:1784-1789.

Bock, B.R., F.J. Sikora, and G.W. Hergert. 1991. Appendix I: An approach for estimating yield response to nitrogen based on nitrogen-rate requirement parameters. *In:* R.F. Follett et al. (ed) Managing Nitrogen for Groundwater Quality and Farm Profitability. SSSA, Madison, WI p.323-332.

Borg, H. and D.W. Williams. 1986. Depth development of roots with time: An empirical description. Trans ASAE 29(1):194-197.

Capurro, E. and R. Voss. 1981. An index of nutrient efficiency and its application to corn yield response to fertilizer: N.I. derivation, estimation and application. Agron. J. 73:128-135.

Follett, R.H., P.N. Soltanpour, D.G. Westfall, and J.R. Self. 1991. Guide to Fertilizer Recommendations in Colorado, XCM-37. Colorado State University Cooperative Extension. Fort Collins, CO.

Hargreaves, G.H. 1975. Moisture availability and crop production. Trans ASAE 18(5):980-984.

Hargreaves, G.H. 1992. Personal Communication.

Hergert, G.W., R.B. Ferguson, and C.A. Shapiro. 1995. Fertilizer Suggestions for Corn. NebGuide G74-174-A. Cooperative Extension, Institute of Agriculture and Natural Resources. University of Nebraska, Lincoln, NE

Jensen, M.E. and H.R. Haise. 1963. Estimating evapotranspiration from solar radiation. J. Irrig. and Drain. Div ASCE 89:15-41.

Meisinger, J.J. 1984. Evaluating plant-available nitrogen in soil-crop systems. *In:* R.D. Hauk (ed), Nitrogen in Crop Production. ASA/CSSA/SSSA, Madison, WI p. 391-416.

Meisinger, J.J. and G.W. Randall. 1991. Estimating nitrogen budgets for soil-crop systems. *In:* R.F. Follett et al. (ed) Managing Nitrogen for Groundwater Quality and Farm Profitability. SSSA, Madison, WI p. 85-124.

Mortvedt, J.J., D.G. Westfall, and R.L. Croissant. 1994. Fertilizer Suggestions for Corn. Service-In-Action 0.538. Colorado State University Cooperative Extension. Fort Collins, CO.

Pierce, F.J., M.J. Shaffer, and A.D. Halvorson. 1991. Screening procedure for estimating potentially leachable nitrate-nitrogen below the root zone. *In:* R.F. Follett et al. (ed) Managing Nitrogen for Groundwater Quality and Farm Profitability. SSSA, Madison, WI p.259-283.

Salazar, L. 1992. Personal Communication.

Schepers, J.S. and A.R. Mosier. 1991. Accounting for nitrogen in nonequilibrium soil-crop systems. *In:* R.F. Follett et al. (ed) Managing Nitrogen for Groundwater Quality and Farm Profitability. SSSA, Madison, WI p. 125-138.

Soltanpour, P.N. Personal Communication.