NUTRIENT UPTAKE: A microcomputer program to predict nutrient absorption from soil by roots[1]

Kenneth Oates and S. A. Barber[2]

ABSTRACT

Soil nutrient uptake by plant roots can be described mathematically. Computer programs (Claassen-Barber, Barber-Cushman) have been developed to solve the mathematical model and predict nutrient uptake. The Barber-Cushman model uses the initial nutrient concentration in solution, the buffer power, the effective diffusion coefficient, and the mean water influx to describe the kinetics of nutrient supply through the soil to the root. The initial root length, the mean root radius, the rate of root elongation, and the half distance between roots are used to describe the root system. Michaelis-Menten kinetics with the maximal influx at high concentration (I_{max}), the nutrient concentration below which influx ceases (C_{min}), and the nutrient concentration in solution minus C_{min} where net influx is one-half I_{max} (K_m), describe influx into the root. For each problem, the program gives the parameter values, a table of relative nutrient concentration with distance from the root and a plot of these data at the final time, a table of nutrient influx with time and a plot of these data, and the calculated nutrient uptake by the plant. Previously only mainframe computer programs were available. The objective of this article is to describe a user-friendly personal computer version of the Barber-Cushman model describing plant nutrient uptake.

Additional index words: **Phosphorus, Potassium, Nitrogen, Diffusion, Soil solution, Ion concentration.**

PLANTS depend on nutrient uptake by the root system to supply nutrients needed for growth. Knowledge about the mechanisms involved in nutrient movement from the soil into the plant has progressed to the point where the process can be mathematically described (Barber, 1984). Computer programs have been developed to numerically solve the mathematical relations involved (Claassen and Barber, 1976; Barber and Cushman, 1981) and predict nutrient uptake by plants grown in soil. These models use parameters and equations that describe the size and morphology of the root system and its change with time, the influx kinetics that describe the relation between nutrient concentration in soil solution at the root surface and net influx, and the nutrients supplied by mass flow and diffusion (Crank, 1956) through the soil to the root surface. Radial geometry is used to calculate the nutrient supply to the root by mass flow and diffusion from a cylinder of soil with a radius equal to the mean half-distance between root axes. Net influx of nutrients as related to their concentration in solution at the root surface is described by Michaelis-Menten kinetics (Epstein, 1972). The model combines the effect of soil nutrients supplied to the root with the Michaelis-Menten kinetics for nutrient uptake by the root to determine the relation between net influx and time. The solution of this relation is nonlinear and is solved numerically using the Crank-Nicolson and Newton-Ralphson techniques (Barber and Cushman, 1981). This relationship can then be

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[2] Post-doctoral research associate and professor of agronomy, Purdue Univ., respectively.

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used with root growth to give calculated nutrient uptake with time. The models have been verified in both pot and field experiments. Close agreement has been obtained between observed and predicted uptake (Barber, 1984).

The initial programs were written to use on a mainframe computer. They have not been easily accessible because the complexity of the program has made it difficult to transfer the program to other mainframe computers; hence, the programs have not been available for educational use. The goal of this article is to briefly describe a user-friendly personal computer version of the Barber-Cushman (1981) program, one that can be used for educational instruction as well as research. Specific objectives are to:

1. Briefly review the mechanistic approach concept
2. Define the parameters used and briefly describe how they are measured
3. Describe user inputs and options available
4. Present an example of input data and output results
5. Discuss some applications of the program

The program is on a diskette and can be readily used on any IBM PC-compatible microcomputer.

THE MODEL

Barber and Cushman (1981) give the assumptions used in calculation of the nutrient transport equations, a discussion of the assumptions, the mathematical development of the equation, the boundary conditions, and the solution technique. A summary of the model and its use is given by Barber (1984). The model requires values for 11 parameters. These parameters describe the kinetics of nutrient supply to the root via the soil, root surface area, mean root radius, root growth rate, water influx, and kinetics of nutrient influx. The parameters are as follows:

C_{li} = the initial nutrient concentration in the soil solution before nutrient uptake (μmol cm^{-3})
b = the buffer power of the nutrient adsorbed on the solid phase for the nutrient in solution
D_e = the effective diffusion coefficient for nutrient diffusion through the soil (cm^2 s^{-1})
L_o = the initial root length (cm)
r_o = the mean root radius (cm)
k = the rate of root elongation (the units depend on the type of root growth; linear growth units are cm s^{-1}, exponential growth units are s^{-1})
r_l = the mean half-distance between root axes (cm)
I_{max} = the maximal influx at high concentrations of the nutrient in solution (μmol cm^{-2} s^{-1})
K_m = the nutrient concentration in solution minus C_{min} where net influx , I_n, is one-half I_{max} (μmol cm^{-3})
C_{min} = nutrient solution concentration below which I_n ceases (μmol cm^{-3})
v_o = the mean water influx into the root (cm s^{-1})

The three soil measurements needed to calculate the soil supply parameters are C_{li}; C_s, the ion concentration on the solid phase that equilibrates within 1 or 2 days with the ions in solution; and θ, the volumetric water content of the soil. Values of C_{li} are obtained by analyzing aliquots of displaced solution from soil columns equilibrated at field capacity water content for 24 h. Values of C_s are measured by exchanging cations with a salt solution or exchanging anions with an anion exchange resin technique and measuring the amount displaced. Volumetric water content at field capacity can be measured gravimetrically and calculated using the soil bulk density. All values must be used on a volumetric basis. To calculate the buffer power, b, several levels of C_s and C_{li} are measured to get $\Delta C_{li}/\Delta C_S$. The effective diffusion coefficient, D_e, can be calculated using the following expression from Nye and Tinker (1977):

$$D_e = D_l \theta f_l / b \quad [1]$$

where D_l is the diffusion coefficient in water. The impedence factor, f_l, which accounts for tortuosity of the diffusion path and any other impedence factors, is obtained by measuring the diffusion rate of a nonabsorbed ion such as Cl^- or estimated by using the following expression by Barraclough and Tinker (1981):

$$f_l = 1.6\theta - 0.17 \text{ for } \theta > 0.12 \quad [2]$$

At θ values < 0.12, use $f_l = 0.25\ \theta$. If only soils are being studied, predicted nutrient uptake from each soil can be calculated using a common set of root parameter values for the crop being considered.

Values for root length, root radius, and growth rate can be obtained by taking measurements from a sequence of plant harvests. Root length, L, may be measured by a line-intersect method (Tennant, 1975). The fresh root weight can be used to estimate the root volume. The mean root radius can then be calculated as follows:

$$r_o = [\text{root volume}/(L\ \pi)]^{0.5} \quad [3]$$

The half-distance between root axes can be calculated as follows:

$$r_l = [\text{soil volume}/(L\ \pi)]^{0.5} \quad [4]$$

Root growth, k, is usually exponential in early growth and linear thereafter to anthesis. Sequential measurements are needed to relate root length with time. Values of k are dependent on soil volume. The default values suggested in the program are for plants growing in a 2.5-L soil volume.

A nutrient solution depletion method (Claassen and Barber, 1974) can be used to obtain the parameters that describe influx vs. concentration by Michaelis-Menten kinetics. The values can be obtained by fitting a least squares program as shown by Claassen and Barber (1974), or they can be obtained graphically from a plot of solution concentration vs. time. Small changes (± 50%) in the values for P or K uptake have little effect on predicted uptake (Silberbush and Barber, 1983a, 1983b). Values for v_o can be calculated from amount of water transpired and the root system surface area.

USER INPUTS

All user inputs are prompted by on-screen questions and are in the following groups:

1. Input-output specifications
2. Single- or multiple-problem selection
3. Linear or exponential root growth selection
4. Soil and root parameter specifications

For the input-output specifications, the user selects from options presented. Output can be sent to the screen, printer, or to a text file, which can be viewed later with a word-processor. A two-line title can be added to the output for identification purposes.

The selection of a single or multiple problem mode depends on the intended use. For classroom demonstration, the single-problem mode is desireable because the program can be terminated after a solution output or another problem can be entered. The multiple-problem mode is useful when several outputs are needed as is the situation for research.

The root growth rate can be either linear or exponential with time (t). Linear growth is calculated as $L = L_o + kt$; exponential growth is calculated as $L = L_o e^{kt}$. The program has three sets of default values for the soil and root parameters that can be used as a starting point. The sets have typical soil parameter values for $H_2PO_4^-$, K^+, and NO_3^- and plant parameters for corn (*Zea mays* L.) (Table 1). The root growth rate value coincides with the growth type chosen. After selecting a default set for $H_2PO_4^-$, K^+, or NO_3^-, the user has the option of changing any of the soil or root parameters.

PROGRAM OUTPUT

For each problem, the program gives a list of the parameter values, a table of relative concentration with distance from the root, a plot of the relative solution concentration with distance from the root at final time (Fig. 1), a table of nutrient influx with time, a plot of nutrient influx vs. time (Fig. 2), and the calculated plant uptake (Table 1). The plots are text files and do not require any additional support for a printer. The relative solution concentration is the ratio of the solution concentration divided by the initial concentration. The table of relative concentration lists values for the number of segments that partition the volume around the root. The first line of the concentration table lists values for the first 10 segments from the root out into the solution. The first value of segment no. 1 is located inside the root. The second value is the concentration for the soil volume next to the root surface. The concentration values in the table are plotted vs. distance from the root. The values are for the specified growth time.

Table 1. Example P default values used for parameters in the nutrient uptake model and program output.

Input values		Default values
D_e	diffusion coeff. (cm² s⁻¹)	2.000E − 09
b	buffer power	2.000E + 02
C_{li}	initial nutrient conc in solution (μmol cm⁻³)	1.500E − 02
v_o	water flux (cm³ cm⁻² s⁻¹)	5.000E − 07
r_l	half-distance between root axis (cm)	3.300E − 01
r_o	root radius (cm)	1.500E − 02
L_o	initial root length (cm)	2.500E + 02
k	root growth rate (cm s⁻¹)	3.900E − 06
I_{max}	maximal influx (μmol cm⁻² s⁻¹)	6.000E − 07
K_m	C-C_{min} when $I_n = 0.5 \times I_{max}$ (μmol cm⁻³)	5.000E − 03
C_{min}	minimal nutrient conc where $I_n = 0$ (μmol cm⁻³)	2.000E − 04
time of root growth (s)		8.640E + 05
	Program output	
UPTAKE (in μmol) by initial root length [L_o]		5.229E + 00
UPTAKE (in μmol) by new roots grown since time = 0		4.518E + 01
TOTAL UPTAKE (in μmol)		5.041E + 01

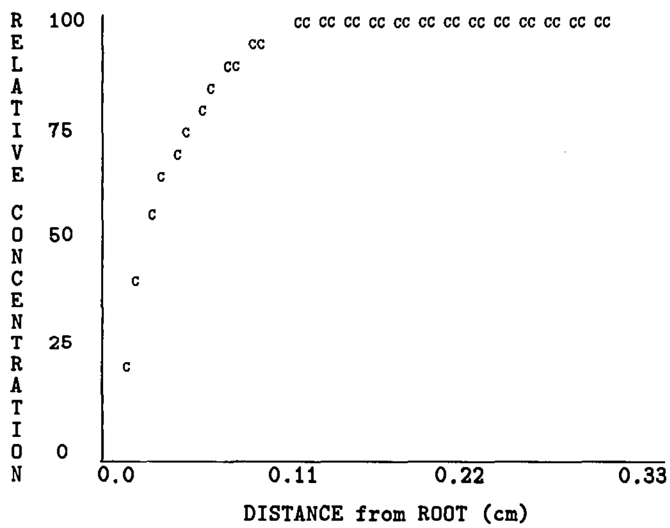

Fig. 1. Phosphorus concentration profile in solution perpendicular to the root at 10 days of growth using parameters given in Table 1.

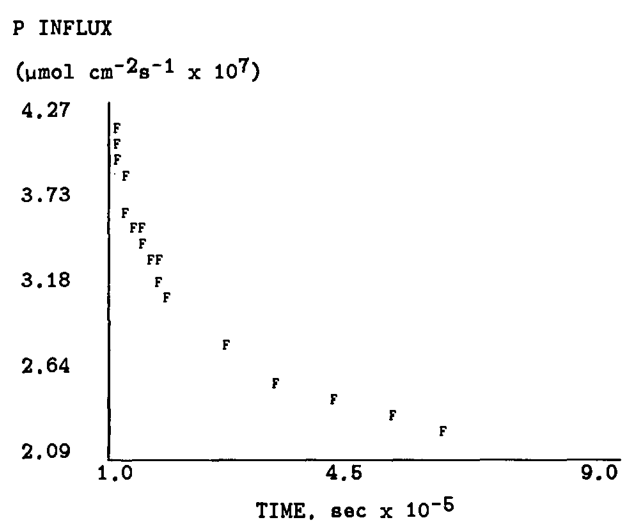

Fig. 2. Relation between P influx and time of uptake using parameters given in Table 1.

Many types of situations and comparisons can be formulated as problems by changing the appropriate soil and root parameter values. For example, changes in the soil or root parameters can be made to examine the parameter sensitivity (Silberbush and Barber, 1983a, 1983b).

The evaluation of a root system with multiple uptake mechanisms can be handled conveniently. For a situation such as a split-root experiment, the analysis would proceed by describing the root system as a group of root fractions. For each fraction, one would then calculate root length, root growth, and other plant parameters and then use the model to calculate uptake for each. Total uptake would be the sum of the uptake of the fractions. A situation that has multiple uptake mechanisms can be handled in a similar manner.

The program is not limited to $H_2PO_4^-$, K^+, NO_3^-, or corn. Default values for these ions were included for convenience. The user has the option to change any value to represent other elements or plant species where parameter values are available.

SUMMARY AND SOFTWARE SPECIFICATION

While this program is intended to be a teaching tool for soil fertility and plant nutrition classes, it can also be used for research. Multiple copies of diskettes can be made for educational use or the program can be copied to a hard disk.

NUTRIENT UPTAKE consists of a compiled file, UPTAKE.COM, totaling 41 K bytes for use with DOS 2.0 on an IBM PC or MS-DOS 3.1 on a PC-compatible computer. The program was encoded in PASCAL and compiled using TURBO PASCAL. It requires 256 K RAM and operates on either a color or monochrome monitor. A printer is optional. NUTRIENT UPTAKE on a diskette and a nine-page document are available for a handling cost of $20. Send requests to S.A. Barber, Agronomy Department, Purdue University, West Lafayette, IN 47907-7899.

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