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Ph.D. degree in Crop and Soil Sciences

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FUNCTIONAL RELATIONS OF ROOT DISTRIBUTIONS WITH THE FLUX AND UPTAKE OF WATER AND NITRATE

By

Robert Martin Aiken

A DISSERTATION

Submitted to Michigan State University in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Department of Crop and Soil Sciences

ABSTRACT

FUNCTIONAL RELATIONS OF ROOT DISTRIBUTIONS WITH THE FLUX AND UPTAKE OF WATER AND NITRATE

By

Robert Martin Aiken

Nitrate leaching reflects poor nutrient retention, poses a hazard to public health and a challenge to solute Field observations and numerical transport theory. simulation of soil-plant interactions are integrated to identify sensitivity of simulated nitrate leaching to errors in predicted root function. Seasonal changes in maize root distributions, canopy development, and gradients in soil water content and carbon dioxide partial pressures were quantified in 1990 and 1991 during water deficits in a field lysimeter under an irrigated rain shelter. Seasonal changes in these parameters and in soil mineral and leached N were determined during 1991 in four field lysimeters subjected to conventional or no-till crop culture. Horizontal and vertical gradients in root intersections with 0.05 (I.D.) x m polybutyrate tubes corresponded with transient 1.4 deficits in plant water supply, and subsequent root proliferation during mid-vegetative growth stages. A horizontal complement to the vertical rooting front is

characterized by exponential distributions of inter-root Geostatistical measures of distances under a row crop. clustered root distributions indicate spatial correlation up to 0.45 m at anthesis. Failure to consider depth-dependent gradients in root xylem potential most likely accounts for systematic bias in soil water depletion predicted by a simplified solution to a cylindrical model of root water uptake. Soil plus root respiration is related to vertical root distributions, but vertical gradients in CO₂ and CO₂ flux fail to satisfy conditions for the steady state assumption. Increased NO₃-N retention in conventional till soil, relative to no-till soil indicates solute partitioning among mobile and immobile regions of soil water may be modified by historic tillage effects. Deviations in NO₃-N concentrations of leachate from seasonal trends coincide extreme high or low drainage flux conditions, with invalidating assumptions of homogeneous pore velocities and solute concentrations. Simulated NO₃-N leaching rates are sensitive to errors in predicted infiltration, canopy dimensions and drainage below the root zone, but are insensitive to reductions in maximum root length density. Managing soil-plant interactions for optimal productivity and solute retention requires accurate simulation of system behaviour when regulation shifts from atmospheric boundary conditions to soil system transport and transformation processes.

to Ann

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Dr. Ritchie graciously offered the field lysimeter under the rain shelter for data collection that provides much substance in this work. Abelardo and Liliana Nufiez-Barrios gave me an early start at this lysimeter. Scott NeSmith's early root observations provided a chance to learn about root spatial structure. I thank Reimar Carlesso for our struggles with neutron probe calibration. He; Mike Robertson; and Huang, Bihu helped with data collection when I had to be away. Jeff Hamelink's and Trish Sweanor's diligent and dedicated efforts account for much of the nitrate leaching, soil water and carbon dioxide data for the Agroecosystem field lysimeters at Kellogg Biological

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PREFACE

Stewardship of the earth is a theme passed down in Western and Eastern traditions. We are given a vision of the good steward in the Christian text " . . . to give them their portion of food at the proper time." Luke 12:42. And from the Taoist text

> Those who esteem the word as self will be committed to the world

Those who love the world as self will be entrusted with the world

Tao Te Ching, 13

Each of us must confront the age-old questions "How do we esteem the world? To whom or what do we give service?"

This work seeks to clarify the limits of our understanding of complex systems. Such pursuit of knowledge is frequently justified by expectations of beneficial applications. Our ability to fulfill these expectations is a measure of our science, our social institutions, and our spirit.

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INTRODUCTION

Nitrate leaching is of practical and theoretical interest. Loss of nitrate below the root zone poses a public health hazard and evinces poor nutrient retention. Nitrate leaching occurs throughout agricultural regions with sandy soils such as western Michigan (Ellis, 1988) and the karst region of Iowa and Minnesota (Hallberg, 1987). Surface waters are contaminated when sediments, phosphorus, nitrates and pesticides are carried off in surface runoff (Baker, 1988).

Management of nitrate leaching is enhanced by knowledge of factors determining synchrony of N supply and plant uptake. A role for simulation in design and management of biological systems is demonstrated by applications to irrigation and bioreactor technology. Effective simulation of complex systems accurately predicts state and output parameters of value to decision-makers for a bounded set of input conditions and system parameters (Manetsch and Park, 1987). Nutrient retention in managed ecosystems is enhanced when knowledge of management and environmental effects on alternative fates of nutrients can be directly interpreted by decision-makers.

Predicting transport of nitrate is confounded by heterogenous distribution of water and N in time and space,

multiple transformations of soil N, and complex interactions among soil, plant, and weather factors. General solutions to equations relating nitrate leaching to management and environmental inputs require simplifying assumptions or detailed specification of the soil-plant-atmosphere system. Solutions to the N leaching problem provide insight to similar problems where biological function is directly and systematically related to transformations and transport of environmental toxins.

Nitrate leaching potential is largely determined by the synchrony of nitrate supply (nitrification and fertilization) with root nitrate uptake (Robertson and Smucker, 1988). In practice, fertilizer N is directly amenable to management. Mineralization of N in organic matter is subject to substrate quality, thermal and xeric constraints (Paul and Clark, 1989).

Soil supply and root uptake of N during exponential vegetative growth is an important determinant of whole plant specific growth rate, as root and shoot growth are alternative sinks for assimilates (Kachi and Rorison, 1989). Root:shoot signals can regulate transpiration and plant growth rates in response to soil dessication (Davies and Zhang, 1991) and soil hardness (Masle and Passioura, 1987). Whole plant growth and development is also modified by root proliferation in soil zones locally enriched in N (Granato and Raper, 1989); and by modification of nitrate reductase activity. Indeed, the specific activity of root uptake is a

fundamental parameter required to simulate optimal allocation of C and N to plant organs for varying levels of radiation and CO_2 (Hilbert et al., 1991). Nitrate leaching potential is reduced and productivity maintained when nitrification rates coincide with root N uptake to maintain optimal shoot N concentration (Hilbert, 1990).

Models of plant growth (Thornley, 1972; Thornley, 1991; Agren and Ingestad, 1987) and ecological succession (Tilman, 1988) are based on the premise of optimal C allocation with respect to soil water and nutrients. Partitioning of assimilates to root, leaf, stem and reproductive organs is optimal when relative growth rates are maximized for a given supply of water, nutrients, and radiation. Soil supply of water and nutrients are simulated in a family of models oriented to agroecosystems (Jones et al., 1986; Addiscott and Wagenet, 1985). Valid models of plant growth and soil supply of water and nutrients require accurate knowledge of root distribution and function.

Root function, as a sorptive sink for water and nutrients, is an important element in the soil water and N balance, and as a determinant of plant growth and development. The classic models of root function assume uniform root distribution (Gardner, 1960; Barber and Silberbush, 1984); though spatial heterogeneity in root distributions is well known (Ogata et al., 1960) with corresponding effects on root function (Gardner 1964). Soil structure effects on root distribution and subsequent

function, constraining the volume of soil explored by subject of current individual roots, is a research 1991; Jones, 1983). Knowledge of root (Passioura, distributions in soil permits microanalysis of soil water depletion zones around individual roots (Lafolie et al., 1991), strengthening our understanding of management effects on soil N.

Simulation of root function in natural and managed ecosystems complements knowledge gained by controlled experimentation. The former approach accounts for systematic variation by quantifying causal relations with systems analysis techniques (Manetsch and Park, 1987). The identifies causal relationships latter approach by partitioning treatment and experimental sources of variation into elements of statistical models, subject to probabalistic interpretation. Indeed, fundamental biophysical phenomena, such as thermal modification of nodal root growth trajectories may underly agronomic treatment effects (Tardieu and Pellerin, 1991). Knowledge gained by either approach can be transferred: directly by validated simulation models, or indirectly, via interpretations of valid principles.

Empirical tests of either simulation or experimental approaches to understanding root systems require accurate quantification of root networks and associated activities. Effective methods should quantify changes in the distribution of roots, water, and nutrients in specified

soil volumes over specified time intervals. Such methods should be non-invasive, submit to acceptable data reduction techniques, and yield parameters that are pertinent to relevant scientific principles. Advances in microvideo technology (Upchurch and Ritchie, 1983; Ferguson and Smucker, 1989) are field-scale techniques that meet these requirements, in situ.

following work addresses the hypothesis that The minirhizotron techniques enable empirical tests of root distributions and activities that are relevent to water Analysis of root function is structured to management. hierarchy of questions regarding address a root distribution, function, and relation to water management in Chapter 1. Spatial analysis of maize root distributions, with implications for root function and plant growth under water deficits, is reported in Chapter 2. Maize root sink strength for water and source strength for CO₂ in a field lysimeter are related to root distributions, soil and atmospheric conditions in Chapter 3. Finally, the relative importance of root distributions to errors in simulated N leaching is reported for a set of field lysimeters in Chapter 4.

CHAPTER 1

NITRATE LEACHING AND ROOT FUNCTION

INTRODUCTION

Root function is systematically related to nitrate leaching. Flux of nitrate beyond the root zone depends on several physiochemical states of the soil profile just prior to an infiltration event. Root functions addressed in this study include:

1) distributed sink for water and N

2) determinants of plant growth and future demand for water and N

3) substrates for decomposition and net N mineralization,

4) soil formation factors, modifying soil structure and transport properties.

These root functions principally affect the state of the soil profile, conditioning nitrate leaching potential rather than actual nitrate flux. It follows that analysis of root effects on N leaching requires consideration of soil-plant interactions in a systematic context. Scientific principles supporting a systems framework for soil-plant management of N are reviewed in the remainder of this chapter.

SYSTEMS THEORY AND SOLUTE TRANSPORT

Structured analysis of a N management system includes identification of performance criteria, functional relations of canopy and root architecture, and use of state equations to simulate mass flow. Systems theory indicates the output [Y(t)] of a system is related to input [X(t)] by the transfer function [G(t)] (Manetsch and Park, 1987)

$$Y(t) = G(t) * X(t)$$
 [1.1]

Thus, knowledge of the transfer function permits prediction of the state of the system at any time for a set of inputs having defined limits. A system is well defined when the transfer function can be written in the form of a state equation

 $\chi(t + 1) = A(t) * \chi(t) + B(t) * \chi(t)$ [1.2] where A and B are matrices defining both system and environmental parameters which influence the system state output parameters, and $\chi(t)$ and $\chi(t)$ are vectors and linear algebra operations apply. A valid state equation for a system describes the condition of the system at all times when specified initial and boundary conditions are known. The relative significance of root function to nitrate leaching can be quantified by implementing the solute conservation equation for specific soil-plant systems.

The equation of state for soil nitrate derives from the solute conservation equation, presented for vertical flow in a dual (mobile, immobile) phase water model (Jury et al., 1991).

$$\begin{array}{cccc} dN_m & dN_{im} & d^2N_m & dJ_wN_m \\ \Theta_m --- + \Theta_{im} ---- & D ---- & - & ----- & r_g \\ dt & dt & dz^2 & dz \end{array}$$
 [1.3]

where $\theta_{\rm m}$ is the mobile phase of soil water, with corresponding solute concentration N_m; $\theta_{\rm im}$ is the immobile phase of soil water, with corresponding solute concentration N_{im}. D is the effective mean hydrodynamic dispersion coefficient, J_w is water flux, r_s is solute reaction rate, z is soil depth and t is time.

Change in solute concentration for these phases results from hydrodynamic dispersion, mass flow, and solute reaction. Sorptive processes can be readily considered by an additional term on the right side of equation [1.3]. Exchange of solutes between mobile and immobile water phases, analogous to macro and micropores, is defined by time-varying concentration gradients and a rate factor (α).

$$\Theta_{im} \xrightarrow{dN_{im}} = \alpha(N_m - N_{im}) \qquad [1.4]$$

Soil supply and root uptake of nitrate are included in the solute reaction term.

 $r_s = r_w * N_m + r_{rn} + r_{mn}$ [1.5] where r_w is root water uptake, r_{rn} is root active uptake of N_m , and r_{mn} is nitrification rate.

Nitrification follows net mineralization of organic matter, which generally proceeds when the C:N ratio of substrate falls below 25:1 (Paul and Clark, 1989). Root N uptake is defined by Michaelis-Menton kinetics (active

uptake) and solute concentration in the transpiration stream (passive uptake).

The water conservation equation--including infiltration, redistribution, evapotranspiration, and drainage components--is implicit in the solute conservation equation.

$$\begin{array}{rcl}
d\Theta_{m} & dJ_{W} \\
--- & = & --- & rW \\
dt & dz
\end{array}$$
[1.6]

Root water uptake (r_W) relates to the capacity of soil water to meet evaporative demand of a plant canopy, as represented by conductivity and water potential gradients across the root-soil interface (Campbell, 1985).

$$r_{W} = \frac{(k_{r} - k_{s})(4 \text{ RLD } z)}{(1-n) \ln(r^{2} * \text{RLD})}$$
[1.7]

where k_r is root hydraulic conductivity, r is root xylem water potential, k_s is soil hydraulic conductivity, s is soil water potential, RLD is root length density, z is soil depth, n is a power of the hydraulic conductivity function, and r is root radius. A simplified solution for root water uptake, assuming a constant root-soil water potential gradient, and a general unsaturated conductivity function was derived by Ritchie (1985).

$$r_W = ------ [1.8]$$

6.68 - ln RLD

where Θ_V is volumetric soil water content, and LL is the lower limit of volumetric soil water extractable by a specified crop for a specific soil.

[1.7] and [1.8] assume uniform Equations root distributions, with cylindrical flow of soil water to the root surface (Gardner, 1960). Water flow is proportional to hydraulic gradients and cylindrical resistance, by analogy, to Ohms law. But root distributions are not uniform (Tardieu et al., 1988b), root:soil contact is not uniform (Kooistra et al., 1992), as required for cylindrical geometry, and water uptake in lower regions of the soil profile are lower than predicted from root length density (Gardner, 1991). Knowledge of root distribution can help modify predicted effects of canopy evaporative demand on the soil water balance.

Root function, root distribution and soil structure are intimately related (Passioura, 1991; Tardieu et al., 1988c). Large massive units of compacted soil, which restrict root penetration, maintain sharp hydraulic gradients between the interiors and surfaces of the ped when root penetration is restricted to clusters around these units (Amato, 1991). Root networks also contribute to the formation of soil aggregates (Russell, 1977; Wang et al., 1986). Root elongation can promote continuity of soil macropores or biopores which promote the transport of water and solutes. These preferential flow paths (Ahuja et al., 1991); have

been reported for structured soil under maize (Warner and Young, 1991). Thus root networks interact with soil structural features to modify root function and soil transport properties.

Transport of nitrate beyond the root zone results from interactions of factors determining the soil water and N balance. Root distributions and activities are important parameters for solving soil water, N, C, and energy balances. The relationship of root function, a distributed sink for soil water and N, with nitrate leaching can be tightly coupled, and necessitates the analyses of root distribution in time and space. Root effects on whole plant growth and development are of particular interest as changing root and canopy distributions determine plant 'demand' for soil water and N.

SOIL NITROGEN AND PLANT CARBON ALLOCATION

Theories of C partitioning in response to varying supply of growth factors, such as water and N, solve plant growth equations for partitioning coefficients that maximize relative growth rates (Hilbert, 1990). A general plant growth equation (Agren and Ingestad, 1987) relates primary productivity to shoot photosynthesis.

$$dW = --- = k \sigma_{s} f_{s} W = Ps$$
 [1.9]
dt

where W is whole plant biomass, k is assimilate conversion

to biomass, σ_s is specific shoot photosynthetic activity, f_s is partitioning coefficient for shoot, and Ps is whole plant photosynthesis. Primary productivity is directly related to root activity (water uptake, or transpiration) under non-stress conditions, when adjusted for vapor pressure deficit (Tanner and Sinclair, 1983).

where k' is normalized transpiration efficiency, T is transpiration, e^{\star} is saturated vapor pressure, and e is ambient vapor pressure. This relation indicates photosynthesis is affected by transpiration rates, as modified by relative humidity conditions. But we know maximal leaf photosynthesis rates approach a linear function of leaf [N] for C3 plants (van Keulen et al., 1989). Also, the fraction of assimilates partitioned to roots and shoots varies with plant nutritional status and soil N supply. Thus we must extend the analysis of plant growth to consider effects of soil [N] on root uptake and tissue [N] effects on assimilation and allocation rates. The effects of soil N supply on assimilation rates and partitioning fractions to root and shoot organs can be related to specific root uptake of N and specific shoot photosynthesis (Hilbert, 1990).

Theory relating soil $[NO_3-N]$ and specific activity of root and shoot organs to C allocation requires simplifying assumptions, but indicates the effect of soil N supply on C
allocation to root and shoot growth. Biomass accumulation during vegetative growth is approximated by an exponential function when root and leaf organs are primary sinks for assimilates. When root and shoot tissue N concentrations (N_p) are identical, the fraction of assimilate allocated to shoot (f_g) is a function of specific root uptake of \dot{N} (σ_r) and specific shoot photosynthetic activity (σ_s) (Thornley, 1972).

$$f_{s} = \frac{\sigma_{r}}{\sigma_{r} + k \sigma_{s} N_{p}}$$
[1.12a]

where root and shoot are the sole sinks for assimilate, by difference we obtain the partitioning fraction for root (fr)

$$f_r = 1 - \frac{\sigma_r}{\sigma_r + k \sigma_s N_p}$$
[1.12b]

This assimilate partitioning relation indicates shoot growth is favored by high root uptake of soil N. As low soil [N] reduces root N uptake, more assimilates are partitioned to roots. Analogous arguments can be made for plant growth responses to soil water availability and evaporative demand. That is, shoot growth is favored when soil water supply is adequate; but root growth dominates under soil water deficits (Smucker et al., 1991). Predicted C allocation patterns under varying soil supply of water and N correspond to compensatory root and shoot growth frequently observed under controlled and field conditions (Russell, 1977).

A root growth model accounting for proliferation, senescence and extensive growth is presented in Hillel and Talpaz (1976).

 $RLD^{j} = (RLD^{j-1} P t) - (RLD^{j-1} D t) - (RLD^{j-1} E t)$ [1.13]

where RLD^{j} is root length density at time 'j', RLD^{j-1} is root length density at time j-1. P is root proliferation in a soil layer, D is root death, and E is root elongation from soil layers above. P and E are modified by exponential declining functions of soil water. Quantifying root growth and function in relation to whole plant development is hypothesized to improve the accuracy of models simulating plant effects on soil N transformation and transport.

IMPLEMENTATION

Solutions to the solute conservation equation [1.3] (Jury et al., 1991) generally follow two approaches:

1) analytic solutions given simplifying assumptions

2) numerical solutions given system specification.

Analytic solutions provide insight to general features of system performance including limits to system stability. Numerical solutions offer more realistic simulation of soilplant conditions, validated by comparison with observed system behavior. Emphasis is given to the latter approach as a general method for testing hypotheses about system structure. Finite element solutions to solute transformation and transport problems can be implemented on mini-computers with much greater flexibility in specifying boundary conditions and system parameters than analytic solutions (Campbell, 1985).

Numerical solutions to the solute conservation equation are conveniently structured into sub-components, or modules. When each module can be described by a governing state equation, the requisite boundary conditions, system and state parameters are clearly identified. Validation of structured numerical solutions can proceed at the module level, simplifying the process of error diagnosis by separating large complex models into smaller component parts. This step reduces the number of potential error sources, thereby aiding the "debugging" process of error diagnosis. The validation approach involves evaluation of the deviation of predicted parameters from actual observations. Modifications of system structure (as opposed to system parameters) may be justified when this deviation is reduced. A modular structure is a means of fracturing complex problems into simpler, coherent components for analysis, then knitting the interacting components together for the integrated solution.

Root function is related to NO₃-N leaching as an explicit term in the solute conservation equation and as a partial determinant of plant demand for water and N. The

range of conditions where N leaching is sensitive to root function can be analyzed when soil-plant-atmosphere interactions are accurately defined. To this end, the remaining chapters are directed.

The solute conservation equation [1.3] suggests a hierarchical structure for analysis of root function and N leaching (Figure 1.1). Knowledge of root distribution in space and time (equation [1.13]) is required for simulating root function, and is analyzed in Chapter 2. Root water uptake (equation [1.7]) is a necessary term in the soil water balance (equation [1.5]) which is evaluated in Chapter 3. Interaction of the soil water and N balance (equation [1.3]), illustrating the relation of root function to N loss by leaching, is evaluated in Chapter 4.



Figure 1.1 Flow chart of the functional relations of root distributions as addressed in Chapter 2 (2), root function in Chapter 3 (3), and flux of water and nitrate in Chapter 4 (4); which illustrate the hierarchical structure of root analysis employed in this work.

CHAPTER 2

SEASONAL TRENDS IN MAIZE ROOT DISTRIBUTIONS

INTRODUCTION

Knowledge of root distributions in time and space is necessary for accurate predictions of root source/sink strength, regulation of transpiration and growth, and of soil structure and solute transport modification processes. The fraction of assimilate allocated to roots is important determinant of relative growth rate and an interspecific interactions such as nutrient acquisition and canopy light exclusion (Tilman, 1988). Distributions of root and soil resistances to water and ion flow are modified by variation in root clustering (Bruckler et al., 1991), diameter (Barber and Silberbush, 1984), and suberization (Russell, 1977). Optimizing soil and water management and gaining inference of interspecific interactions are strengthened by knowledge of factors regulating root system development (Klepper et al., 1983).

Root morphology appears to be controlled by the interactions among root tip meristems, localized soil environments, and transport of nutrients, assimilates, and growth regulators among root and shoot organs (Kuiper, 1987). Root proliferation and elongation rates are known to

respond to temperature, anoxia, mechanical impedence, water deficits, plant phenology, and the relative nutrient status of both plants and soil (Russell, 1977). These root growth responses include changes in diameter, elongation rates, branching frequencies, and permeability.

Soil thermal and hydric conditions are known to modify the geometry of root distributions (Allmaras and Nelson, 1973; Kuchenbuch and Barber, 1988). Higher inter-row soil temperatures stimulated root proliferation and branding into the warmer inter-row region in a growing season with lower soil termperatures, but not in a growing season with higher soil temperatures (Allmaras and Nelson, 1973). Fortin and Poff (1990) demonstrated a positive thermotropic growth response of maize roots. Curvature of root growth towards a thermal gradient were not related to passive thermal growth effects, which would favor growth away from warmer Tardieu and Pellerin (1991) found that mean conditions. soil temperature, during the 100 degree days after maize nodal root appearance, could account for differences in root growth trajectory associated with differences in sowing mulching, experimental site location date, and vear treatments. Clearly, the horizontal component of root growth trajectories can be modified by soil thermal conditions.

Root and shoot biomass are functionally linked as alternative sinks for assimilate. The relative fraction of photosynthates allocated to roots and shoots is subject to

ç 1 g r W a a 1 b f n f d ha D: dj gi nc 19 дШ gs re 19

genetic regulation, and environmental modification. Genetic advances in wheat are partially attributed to reduced carbon allocation to root organs, without change in water extraction, rooting depth, or water use (Siddique et al., Increased harvest index and water use efficiency of 1990). grain for modern wheat varieties were attributed to lower root:shoot ratios, relative to older wheat varieties. Soil water deficits are known to increase the fraction of assimilate partitioned to root organs (Russell, 1977, Zhang and Davies, 1991); though extended water deficits reduce leaf expansion, photosynthetic capacity and total root relative to water sufficiency. biomass Environmental factors such as soil structural characteristics can also modify root distributions (Passioura, 1991).

Vertical distributions of root length density are frequently approximated by exponential functions of soil depth. This distribution results from the geotropic growth habit and lateral formation of root systems developing under minimal stress in homogeneous soils. The distribution of distance separating roots, an important determinant of ion and water absorption, is skewed, with exponential to lognormal distributions (Logsdon and Allmaras, 1991; Tardieu, 1988b). Interactions of clustered roots, with large gaps among clusters are neglected by models of root function that assume water and solutes traverse uniform distances to reach the root surfaces (Passioura, 1991; Lafolie et al., 1991). The geometric structure of root networks reflect the

plasticity of their growth responses to heterogenous soil conditions.

Exponential distributions of distances separating roots provide positive evidence of clustered root distributions; for many roots within the cluster are separated by small distances, while large distances separate the clusters of roots. Root clusters can also be diagnosed by geostatistic techniques, such as spatial correlation.

spatial correlation indicates that the Positive presence or absence of a root at a given location is positively correlated with root distribution in the locality. The absence of spatial correlation indicates that the presence of a root provides only random information about root distributions in the locality (Peck, 1983). Indeed, the presumption that root intersections at a plane of observation are correlated with similar root distributions in the bulk soil is a variation on the theme of spatial correlation.

Non-destructive, repeated measurements of root spatial distribution can characterize seasonal changes in root clustering and inter-root distances. By sampling identical soil volumes over time, the statistical dilemma of relating spatially variable sampling locations is avoided. Indeed, characterizing the spatial structure of root distributions can yield insight to biophysical implications of root function (Lafolie et al., 1991). Geostatistic analysis also provides optimal spatial interpolation, for mapping spatial

distributions with known variance structure (Warrick et al., 1986).

Seasonal and spatial trends in root distributions can be quantified by repeated measure of root intersections with minirhizotron access tubes (Smucker, 1990). Concurrent determination of canopy development and soil water depletion permit synchronous analyses of root and shoot growth activity. The following research was conducted to characterize the spatial structure of root distributions and interpret the biophysical consequences.

METHOD AND MATERIALS

Crop culture and biomass distribution

Maize (Zea mays L., hybrid Pioneer 3573) grown in a 1.4 x 1.4 x 1.8 m non-weighing lysimeter (Figure 2.1) under a rain shelter (NeSmith and Ritchie, 1992) was subjected to extended water deficits during the reproductive stages of development in 1986, and the vegetative growth stages in 1990 (Table 2.1, Ritchie et al., in preparation). A third data set was collected during water deficits extending through the vegetative and reproductive growth stages in 1991 (Table 2.1). A Spinks sand (Sandy, mixed, mesic Psammentic Hapludalfs) was packed into the lysimeter and associated 4.6 x 6.2 m field plot beneath the automated rain shelter. The bulk density and corresponding depth intervals of soil layers are 1.3 Mg m⁻³, 0.0 to 0.25 m; 1.27 Mg m⁻³, 0.25 to 0.8 m; 1.46 Mg m⁻³, 0.8 to 1.4 m; 1.49 Mg m⁻³, 1.4 to 1.8 m. The lysimeter was bordered by crop on all sides. Cultural practices are summarized in Table 2.1.

Lysimeter instrumentation

Polybutyrate minirhizotron (MR) tubes (0.05 x 1.4 m) were installed perpendicular to crop rows and parallel to the soil surface (Figure 2.1). Duplicate tubes at each depth provided access for micro-video cameras (Ferguson and Smucker, 1989) and neutron probe (Gardner, 1986). Upper surfaces of the MR tubes are 0.50, 0.72, 0.90, 1.07, 1.27, 1.43 and 1.60 m below the soil surface. Paired stainless steel rods installed as vertical wave guides for time domain reflectometry (TDR, Topp et al., 1982) were installed in the surface 0.15 and 0.3 m of the soil at locations 0.3, 0.6, 0.9, and 1.2 m from the east edge of the lysimeter during 1991. No TDR wave guides were installed in 1986 nor in 1990.

Boil water

Soil water depletion was determined by neutron thermalization at three to seven day intervals following initiation of water stress in 1990 and 1991. The neutron probe was inserted in two vertical tubes centered in the crop row and interrow in 1990, or in the horizontal MR tubes, in 1991 (Figure 2.1). Volumetric soil water contents were determined by computing the ratio of counts observed

Parameter	1990	1991	
Planting date (Day of Year)	144	156 ? "1777	
Water deficit initiation	179	179	
Water deficit termination	220		
Plant population (Plants m^{-2})	7.14	9.18	
Nitrogen (g N m ⁻²)	20.0	12.0	
Phosphorus (g P m ⁻²)	18.0	6.0	
Potassium (g K m ⁻²)	6.0	6.0	

Table 2.1 Maize cultural practices for lysimeter in rain shelter containing Spinks sand at Kellogg Biological Station

Table 2.2 Day of year for Maize phenologic development for lysimeter in rain shelter containing Spinks sand at Kellogg Biological Station

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Phenological stage	1990	1991
Emergence	152	156 ?
Eight leaf	191	194
Anthesis	212	217
Grain fill	230	238



Figure 2.1 Instrumentation for repeated measurements of root distributions and soil water in a non-weighing lysimeter under an irrigated rain shelter.

at 0.15 m intervals in vertical or horizontal access tubes, to standard counts. This count ratio is related to volumetric soil water content by a field calibration procedure. The apparent dielectric constant, as determined by TDR, is related to soil water content by the Topp equation (Topp et al., 1982)

$$\Theta_{v} = -0.053 + 0.0282 * K_{a} - 0.0005 * K_{a}^{2} + 0.0000043 * K_{a}^{3} [2.1]$$

where $K_a = (ct/L)^2$, $t = (B-A)/(V_p*c)$, c is the propogation of an electromagnetic wave in free space (30 cm/nsec). L is the length of the wave guides inserted into the soil. V_p is the experimentally determined propogation velocity of the cable. B is the distance of the reflected pulse from the pulse generator, taken as the tangent made by the zero and positive slopes traced in the waveform. A is the distance separating the pulse generator from the junction of the TDR cable and wave guides, taken as the point preceeding the large negative slope in the waveform. Spatial and analytic components of soil water variability are computed as the standard deviation of replicate observations at identical depths.

Functional soil properties describing the capacity of the soil to supply water can relate soil water content and root distributions to water deficits (Ritchie, 1985). The drained upper limit (DUL) water content was determined by constant soil water distribution following saturation, when active roots were absent. The lower limit (LL) of volumetric soil water extractable by maize was determined after 73 days of drought stress, when the soil water distribution became static even though active roots were present. Available water (AW_i) for soil layer i was computed as the difference between volumetric soil water content (Θ_{vi}) and the lower limit (LL_i)

$$AW_{i} = \Theta_{vi} - LL_{i} \qquad [2.2]$$

The quantity of available water stored in a soil layer (SAW_i) is the product of available water and layer thickness (dz). The quantity of available water stored in the rooted soil profile (SAW_r) is the sum of stored water in all soil layers within the rooting depth, where z_r is maximum depth of rooting.

$$SAW_{r} = \sum_{i}^{i=z_{r}} SAW_{i}$$
 [2.3]

The quantity of available water stored below the active root zone (SAW_V) is the sum of stored water in all layers from the rooting depth to the lysimeter base (z_b) .

$$SAW_{V} = \sum_{i=z_{r}}^{i=z_{b}} SAW_{i}$$
 [2.4]

Canopy development

Canopy structure was determined for three representative plants from each of two rows. Date of leaf maturation and senescence, mature leaf length and width, height to top mature ligule, and reproductive development phases were parameters selected to quantify green leaf area (GLA), and biomass of leaf and stem. Green leaf area is computed as a time (t) dependent function for each plant:

$$i=m$$

 $GLA(t) = \Sigma (L_{i} \times W_{i} \times 0.75)$ [2.5]
 $i=s$

where L_i and W_i are the length and width of the "ith" leaf, m is the top mature leaf number, and s refers to the top senescent leaf number. Confidence intervals about the canopy green leaf area index (GLAI(t)) and height to top mature ligule (H(t)) are computed from GLA(t) and plant population.

Root intersections with MR tubes were recorded six to ten times during the growing seasons by microvideo cameras (Circon in 1986 and 1990; and Bartz Technology Co. 650 Aurora Ave. Santa Barbara CA 93109 in 1991). Video image dimensions for the Circon camera are 12 x 18 mm, for the Bartz camera, 13.5 x 18 mm. The longer frame dimension is perpendicular to the MR tube. Active roots were identified by high light reflectance, opaque appearance and structural integrity. Senescent roots observed prior to crop establishment were excluded from root counts as were translucent roots and roots with low reflectance. Root number (RN) values were determined by computing the number of root counts (N) per unit area (A) of the soil-MR tube interface, and converted to root length density (RLD) by the following relation, suggested by Upchurch and Ritchie (1983)

$$RLD = Nd/Ad$$
 [2.6]

where d is the MR tube outer diameter. This relation assumes the mean length of roots intersecting the volume occupied by the MR tube would be equal to the outer diameter of the MR tube, if the soil were not displaced by the MR tube (Upchurch and Ritchie, 1983).

Root distribution

The rooting front, e.g. initial root arrival at a given depth, was determined by the reduction of stored soil water at rates exceeding 0.05 mm day⁻¹ for a 0.15 m soil layer, or by the initial root observation at the soil-MR tube interface. Root proliferation (Rp) during a sampling interval was computed for each MR tube as the rate of change in RN with respect to time (t)

$$Rp = dRN/dt$$
 [2.7]

Vertical distributions of mean root intersections observed for each horizontal MR tube were analyzed as a logrithmic function of soil depth:

$$RN = a + b \pm log(z)$$
 [2.8]

where RN is root intersections cm^{-2} , z is soil depth (m), a and b are empirical coefficients. Vertical trends in root distribution, quantified by Equation [2.8] were used to adjust root observations for geostatistical analysis (described below). Seasonal trends in root distributions were quantified by multiple linear regression of RN on simple and interacting effects of day of year (DOY), (DOY)², and log(z). A second order model of seasonal trends in root distributions was used, reflecting declining root proliferation rates during reproductive growth stages after rapid root development during vegetative growth.

The fraction of soil contained in gaps between roots, e.g. distances separating root observations, was determined for the upper MR tube. These root separation distances (RSD) were quantified relative to the time elapsed since the initial root arrival at the MR tube, e.g. days after interception (DAI). Distributions of distances separating roots were computed as relative frequency functions of distance separating roots at the MR tube surface:

$$F_{rsd}(i) = \frac{N_{rsd}(i)}{N_{f}}$$
[2.9]

where $F_{rsd}(i)$ is the relative frequency of video frames contained in MR transects with a root separation distance (RSD) of length "i", $N_{rsd}(i)$ is the sum of video frames contained in continuous segments of MR transects with root separation distance of length "i", and N_f is the total number of microvideo frames recorded in the set of MR transects. Isolated video frames with intersecting roots were included in the smaller of the adjacent RSD intervals. Contiguous video frames with intersecting roots were included in RSD intervals with dimension of the video frame width (12 or 13.5 mm). The distribution of RSD was also computed as a cumulative frequency function of the separation dimension:

$$CF_{rsd}(i) = \Sigma F_{rsd}(i) \qquad [2.10]$$

where $CF_{rsd}(i)$ is the cumulative frequency of video frames contained in root separation distance intervals smaller than the length "i" for the set of MR tubes.

Geostatistical analysis

Spatial analysis of root distributions is motivated by the hypothesis that root function is dependent on geometric arrangements of roots. Geostatistical techniques quantifying spatial correlation provide a means of diagnosing clustered root distributions. These techniques are well suited for the analysis of MR root intersections, as large volumes of data are readily reduced to general relationships that describe structural features of root spatial distributions. Further, geostatistical analysis provides a method for the optimal interpolation among sampling points, yielding 'maps' of root distributions.

The degree of spatial correlation is most readily quantified by semivariograms. These statistical functions are typically presented as a graph of the semivariance statistic (analogous to variance), computed as a function of distance separating pairs of observations (Vieira et al., 1983). The following equation was applied to the MR images:

$$gamma(h) = 1/2N(h) \Sigma [RN(i) - RN(i+h)]^2$$
 [2.11]

Here gamma(h) is semivariance at separation distance (h), N(h) is the number of paired observations separated by distance (h), RN(i) is root number at location "i", and RN(i+h) is root number at a location separated from "i" by distance "h".

A semivariogram characteristic of spatial correlation indicating, for example clustered root distributions, would be indicated by a positive increase in semivariance with distance separating pairs of observations. This means the variability of root intersections along the MR tube increases as distances separating observation points The range of spatial correlation, roughly increases. corresponding to the dimension of root clustering, is indicated by the separation distance at which semivariance approaches a constant value. This structural variance, or "sill" represents a spatially adjusted estimate of the population variance for observations separated by distances greater than the range. Observations separated by this characteristic distance are considered spatially The semivariance extrapolated from independent. the smallest separation distance to zero separation distance is known as the "nugget" effect. A low nugget:variance ratio is a positive indicator of spatial correlation.

Constructing a semivariogram from observations, such as root intersections with MR tubes, relies on the assumption that the mean root distribution is constant throughout the soil profile (Aiken et al., 1991). To satisfy this assumption, vertical trends in root distributions are removed by subtracting functions characterizing these trends, e.g. exponential functions of soil depth (equation [2.8]), known to describe vertical root distributions in the soil profile.

$$RN'(x,z) = RN(x,z) - [a + b*log(z)]$$
 [2.12]

Here RN'(x,z) is detrended root number for horizontal location 'x', and vertical position 'z', corresponding to a RN observation at the same position. Equation [2.8] is used to represent the vertical trend in RN. This 'detrending' process is verified when the semimvariogram of detrended data exhibits a stable structural variance; but a semivariogram constructed from original data maintains increasing semivariance through the range of sampling observations.

Knowledge of spatial correlation, as quantified by the semivariogram, permits interpolation, or "kriging", among observation points. Neighboring observations are combined with weights defined by the semivariogram. The relative weight of observations decreases with distance from the interpolation point. Block kriging was used to interpolate RN for a specified soil volumes. When the kriging procedure uses semivariograms derived from detrended data, vertical trends from equation [2.8] were added back to kriged value for the final estimate of RN.

Residual error from each model of vertical root distributions can be partitioned into spatially correlated geostatistical random components by analysis. and Anisotropic semivariance, a function of distance and direction of vectors separating root observations, is computed from residual error for each root profile. When semivariance is not related to the direction of the vector separating root observations, theoretical models, such as the spherical isotropic model described below, are fit to the semivariogram obtained by pooling semivariance from alldirection class intervals.

 $gamma(h) = C_0 + C[1.5(h/A_0) - 0.5(h/A_0)^3 \text{ for } h < A_0 \quad [2.13a]$ $gamma(h) = C_0 + C \qquad \text{for } h > A_0 \quad [2.13b]$

where gamma(h) is the semivariance computed as a function of distance (h) separating paired observations, C_0 is the nugget variance, C is the structural variance, and A_0 is the range of spatial correlation. Interpolation of non-random root distributions is presented by summing positional trends, as described by equation [2.8], and kriged residual errors, based on the theoretical model of the semivariogram. Root length density is predicted for blocks of soil (0.05 x 0.05 m) by adding RN' predicted by the positional trend to the kriged value obtained from detrended data. The (0.05 x 0.05 m) dimensions of interpolated soil blocks provide a convenient estimation unit, intermediate between the minimum observation unit (0.012 m) and scale of soil water sampling (0.15 m).

RESULTS

Seasonal trends

Root distributions of maize declined exponentially with depth in the Spinks sand for each of the three years (Figure 2.2A-C). Stratified root proliferation at 1.3 and 1.6 m depths, but not at 1.1 and 1.45 m depths modified the exponential distribution during reproductive development for drought stress conditions. Seasonal trends in root development are quantified by multiple regression of RN on simple and interacting effects of soil depth and day of year (Figures 2.3A-C). Extensive growth of the rooting front and root proliferation in certain soil layers are related to soil water depletion in horizons at greater soil depths.

The rate of root vertical extensive growth into soil layers defines the rate of movement of the rooting front. The vertical position of the rooting front defines the lower boundary of rooted soil, used to quantify water stored in the rooted soil profile (SAW_r, equation [2.3], and in soil underlying the rooted zone (SAW_v, equation [2.4]). Root proliferation, resulting from extensive growth of initiated root laterals, occurs in soil layers above the vertical

position of the rooting front. Root water uptake capacity for a soil layer is modified by the number and geometric distribution of root laterals intersecting that layer. Thus, the vertical position of the rooting front, and the geometric distribution of roots proliferating above the rooting front modify the quantity of water available to plants, and water uptake capacity of plant root systems.

Root arrival at 1.1 m depth, was observed by the soil water depletion method (detected by neutron thermalization) 15 days prior to root intersection with the MR tubes for the 1991 season (Figure 2.4B). The greater sensitivity to root arrival by the soil water depletion method is attributed to the larger cross sectional area (0.15 mx1.4 m) sensed relative to the microvideo camera (18 mm x 1.4 m). Since few roots are required to initiate detectable water removal (Passioura, 1991), the probability of detecting root arrival should be proportional to the cross section of the soil surface detected, and subject to detection limits of the This result is consistent with reports sampling system. that soil water depletion occurs at slightly greater depths than observation of grain sorghum roots by triplicated soil core samples (42 mm i.d.) at depths exceeding 1.0 m (Robertson et al., in press).

The rooting front progressed at a rate of 29 mm/day, from day 183 to day 210, in 1991 (Figure 2.4A), coinciding with soil water depletion in upper soil layers and increasing depth of water uptake (Figure 2.4B). For example,



Figure 2.2 Distributions of maize roots with respect to soil depth (A) 1986, water deficits during the reproductive phase, (B) 1990, water deficits during the vegetative phase, (C) 1991, water deficits during the vegetative and reproductive phases.



 $RN = -2.042 + 0.0072^{\circ}Day + 0.693^{\circ}z - 2.289^{\circ}log(z) R^{2} = 0.841$

 $RN = -3.25 + 0.0125Day + 0.849z - 0.000059Day^2log(z) R^2 = 0.844$



RN = -1.46 + 0.645z + 0.000022Day² - 0.0095zlog(Day) R² = 0.77

Figure 2.3 Seasonal trends in maize root development (A) 1986, water deficits during the reproductive phase, (B) 1990, water deficits during the vegetative phase, (C) 1991, water deficits during the vegetative and reproductive phases.

on day 199, 52 mm of stored available water were available in the 1.3 m of soil containing roots, corresponding to 50% of the maximum water storage capacity (IBSNAT, 1985). Loss of leaf turgor was observed at this phase of vegetative growth; this period corresponds with maximum root proliferation at the 0.5 m depth (Figure 2.5A). By day 210, root extension (indicated by soil water depletion, Figure 2.4A) to a depth of 1.5 m coincided with root proliferation at 0.7 m (Figure 2.5A) and 1.6 m (Figure 2.5B). Loss of leaf turgor and leaf rolling were observed on days 213 and 217 despite root water uptake from depths of 1.6 m prior to day 213, and 92 mm of available water stored in the rooted zone. These data suggest water supply to shoots was limited by root distribution in soil layers containing available water.

The visual evidence of plant water stress while root were presence in soil layers with available soil water contradicts the interpretation of SAW_r (equation [2.3] as a measure of the quantity of water available to plants. The presence of roots in water-bearing soil layers was not sufficient to prevent loss of turgor, observed on days 199, 213 and 217. We infer plant water status was modified by the horizontal gradients in distribution of roots and water in the soil. Thus, transient plant water deficits can result from non-uniform distribution of root growth in soil layers during a drying cycle. The remainder of this chapter is devoted to methods for quantifying spatial variability in root distributions.



Figure 2.4 (A) Maize rooting front detected by soil water depletion and MR root intersections and (B) available water stored in rooted soil and in soil underlying the root zone for water deficits during 1991 vegetative and reproductive phases.



Figure 2.5 Maize root proliferation rates for water deficits during vegetative and reproductive phases in 1991 (A) 0.5 to 0.9 m depths, (B) 1.07 to 1.6 m depths.

Root spatial Distribution

The spatial distribution of roots can be quantified by 'kriging'. Application of this interpolation procedure involves computing a weighted average of root number (RN) observations from the 16 MR video grams which are nearest each 0.05×0.05 m cell in the soil profile observed via horizontal MR tubes. Weighting factors are derived from a theoretical semivariogram (e.g. equation [2.13a and b]), obtained by geostatistical analysis. Vertical trends in RN, quantified by equation [2.12], are added to kriged values derived from detrended MR observations to obtain the maps of root distributions presented in Figures 2.6 - 2.8.

Horizontal and vertical gradients in RN are clearly indicated for mid-vegetative growth at eight leaf stage, Figure 2.6A. Spatial patterns of the maize root system subjected to water deficit conditions, were dominated by accumulations below the root system rows. Initial rootextension during the eight leaf stage occurred under crop rows, resulting in few root clusters in the inter-row region which was largely unexplored by roots. Root system development increased RN under crop rows by anthesis, and expansion into the region between rows, reducing the volume of soil not explored by roots. Clustered root distributions beneath the rows persisted through the grain fill growth stage, although additional soil exploration by the expanding root system and root senescence resulted in more uniform soil exploration with time.



Figure 2.6 Maize root distributions in a Spinks sand derived from exponential trend and semivariograms for 1991 water deficit during the vegetative and reproductive phases (A) Eight leaf growth stage (Day 194), (B) Anthesis growth stage (Day 217), (C) Grain fill growth stage (Day 238).



Figure 2.7 Maize root distributions in a Spinks sand derived from exponential trends and semivariograms for 1986 water deficit during the reproductive phase (A) Eight leaf growth stage (Day 191), (B) Anthesis growth stage (Day 212), (C) Grain fill growth stage (Day 238).





Figure 2.8 Maize root distributions in a Spinks sand derived from exponential trend and semivariograms for 1990 water deficit during the vegetative phase (A)⁻ Eight leaf growth stage (Day 191), (B) Anthesis growth stage (Day 212).

The spatial structure of detrended root observations exhibit clear seasonal characteristics that are consistent among water stress conditions (Table 2.3). Variability of root distributions--estimated by structural variance-increased during root proliferation, associated with plant developmental phases. The trend of increased spatial heterogeneity is clearly indicated by an eight-fold increase in structural variance from the eighth leaf growth stage through grain fill growth stages during the 1991 season.

Table 2.3 Semivariance analyses of detrended data for maize root spatial structure within a Spinks sand under a rain shelter at the Kellogg Biological Station

Growth	Theoretical	Variance			Coef. of		
Stage	Model	Nugget	Struct	. N/S	Range	Det. (R ²)	
1986						a da	
Eight Leaf	Linear	0.142				0.091	
Anthesis	Spherical	0.232	0.282	0.82	0.45	0.256	
Grain Fill	Spherical	0.274	0.362	0.76	0.31	0.679	
1990							
Eight Leaf	Exponent.	0.021	0.034	0.62	0.33	0.325	
Anthesis	Spherical	0.091	0.156	0.58	0.31	0.584	
1991							
Eight Leaf	Spherical	0.018	0.029	0.62	0.79	0.312	
Anthesis	Exponent.	0.086	0.139	0.62	0.30	0.358	
Grain Fill	Exponent.	0.121	0.243	0.50	0.21	0.779	
N/S is the	ratio of Nug	get Var	iance t	o Stru	ctural	Variance.	

Structural variance also increased with plant developmental phases in the 1986 and 1990 seasons. The positive correlation of structural variance with plant and root developmental phases is consistent with field observations of seasonal increases in spatial variability of root distributions.

Increased root spatial heterogeneity is matched by seasonal decreases in the range of spatial correlation. The range of spatial correlation extended to 0.79 m at the eight leaf growth stage in 1991. This distance roughly corresponds to the distance separating root clusters under crop rows, and the absence of roots under the furrow (Figure 2.6A). By time of anthesis, the range of spatial correlation decreased to 0.3 m, a distance corresponding to half the row spacing distance--equivolent to soil zones below crop row and The ratio of nugget to structural variance, furrow. another indicator of spatial correlation, decreased slightly from anthesis to grain fill growth stages in all This positive indication of three years (Table 2.3). spatial correlation corroborates visual evidence of clustered root distributions (Figures 2.6-2.8). This result indicates the assumption of uniform root distribution is no more valid after root proliferation than earlier phases of root system development.

Models pertaining to soil water and nutrient managment can gain accuracy in simulated root function by considering effects of clustered root distributions on uptake of water
and solutes. Root quantification under field conditions can be improved by ensuring sampling distances exceed the range of spatial correlation expected for the respective root development phase. The structural variance reported here can be interpreted as spatially independent estimates of variance in RN at three stages of phenological development. Such estimates are useful for determining the number of sampling and experimental units required for detecting experimental treatment effects (Steel and Torrie, 1980 pp. 164-166).

Diagnosis of vertical trends in mean RN during vegetative growth is confirmed by lower RN values with respect to soil depth (Figures 2.6A, 2.7A, and 2.8A). The magnitude and spatial heterogeneity of RN increased during early and late reproductive growth (Figures 2.6B-C, 2.7B-C, and 2.8B). This seasonal trend towards increasing heterogeneity is attributed to the sensitivity of root proliferation to locally variable soil conditions.

Geostatistical analysis confirms our expectation of clustered root distributions, for spatial correlation, a diagnostic for clustered distributions (Vieira et al., 1983), is indicated by nugget to structural variance ratios of less than 1. The range of spatial correlation observed at reproductive growth stages, 0.2 to 0.4 m (Table 2.3), indicates the the distance from any given, or reference video frame where the probability of root intersection approaches a random distribution. Within this range of

spatial correlation, the frequency of root intersections are expected to be more similar to the value observed in a reference frame. Thus, video frames with root intersections are likely to be neighbored by frames that also record root intersections. The corollary also holds: video frames adjacent to a frame devoid of roots are also likely to lack root intersections.

Confirmation of horizontal and vertical root clustering indicates that the range of distances which influence the diffusive resistance to water and solute flow to root surfaces is not uniform, as frequently assumed in solutions to cylindrical flow models of root water uptake (Gardner, 1960, Ritchie, 1985; Passioura, 1991). These and additional concepts regarding the application of heterogenous root distributions to simulations predicting nutrient and water uptake require rethinking of the source codes used for planning soil and water management strategies.

Root separation distances

During the early phases of root proliferation, root separation distances (RSD) are large at soil depths from 0.5 to 0.72 m (Figure 2.9). Two weeks after the first intersection of roots with MR tubes (14 DAI) 30% of the MR transects was contained in RSD lengths of less than 0.03 m, 34% of the soil transects was included in RSD lengths ranging from 0.03 to 0.18 cm, and RSD lengths exceeding 0.18 m comprised the remaining fraction of the transects. Five



Figure 2.9 Cumulative freqency distribution of distances separating maize root observations at 0.5 m and 0.72 m depths in a Spinks sand during periods of water deficits in 1991. Root observations were taken at 194, 217, and 238 days, which corresponded to 14, 37, and 58 days following the first intersection (DAI) of roots with MR tubes.

weeks after root interception (37 DAI), all RSD lengths were less than 0.12 m with 70% of the soil containing roots within 0.02 m of each other. Eight weeks after root interception (58 DAI), 90% of the soil contained roots within 0.03 m of each other. We conclude that the distribution of distances separating roots is exponential during initial root emergence at a horizontal plane, with degree of skew decreasing following root proliferation and extensive growth.

DISCUSSION

The declining exponential distribution of roots through the soil profile is consistent with a simple conceptual model of root system development.

$$dz/dt = k1$$
 [2.14a]

$$dx/dt = k2$$
 [2.14b]

$$dRN/dt = k3$$
 [2.14c]

where dz/dt is the mean vertical displacement of a root tip, dx/dt is mean horizontal displacement, dRN/dt is mean rate of root proliferation, k1, k2 and k3 are constants, or variates subject to genetic and environmental modification. Thus, the notion of a rooting front is extended horizontally and includes a description of root proliferation sequences. RN decreases with depth at a given time interval, and increases with time, for each depth. The distribution of root separation distances (RSD) is conditioned by a mean horizontal displacement, resulting from geotropic root trajectories, planes of weakness within the soil matrix, and weather conditions.

Time dependent changes in the root proliferation front increasing frequencies of characterized by root are intersection with the horizontal plane, and decreasing frequencies of inter-root distances for a given soil depth. The horizontal dimension of root proliferation defines the horizontal limit of the volume of rooted soil. Localized soil water depletion at the root proliferation front can in transient water stress, altering stomatal result resistance, C assimilation and allocation patterns, root initiation frequencies and formation of suberin layers in aging roots. The geometry of root proliferation, and corresponding function, is constrained by plant stem distributions, root branching patterns, and environmental modification of root tip growth trajectories.

Uniform root trajectories would result in constant horizontal displacement of vertical laterals relative to the parent root, but the distribution of distances among laterals would be non-uniform for roots with identical trajectories but varying positions of initiation along the parent root. Since initial roots in rooting proliferation are expected to develop directly below the stem, initial distribution of roots should correspond with clusters under stems and distances between clusters dimensionally similar to distances separating plant stems i.e. row spacing. This initially results in a skewed distribution of inter-root distances. As root proliferation proceeds, the population of roots at a given depth increases and gaps between roots decrease.

This conceptual model of root system development suggests the fraction of soil contained in large gaps between roots is greatest at the earliest stages of root proliferation and agrees with values measured in this study, (Figure 2.9). Mean inter-root distances decrease with root proliferation and horizontal displacement, especially in the Distribution of soil contained in more shallow soils. classes of root separation distances (RSD) is skewed during initial phase of root elongation, which could be the described by an exponential function of decreasing RSD but approaching a normal distribution subsequent to greater root This shift in the distribution of RSD is proliferation. consistent with Erlang distributions, applied to simulation of time delay processes (Manetsch, 1976). As the frequency of roots increases, the distribution of RSD can also shift from exponential towards normal distributions.

The skewed distribution of roots, counterpart to skewed distribution of distances separating roots, also follows from a geotropic model of root system distribution. As roots proliferate, distances between pairs of roots become more uniform. It follows that simplifying assumptions of homogeneous root distribution are most erroneous during intermediate phases of root proliferation. Failure to consider the distribution of distances separating spatially

variable roots (Figure 2.10), will confound estimates of water and nutrient uptake, including diffusion of immobile ions to root surfaces, and interactions among roots.

A conceptual model of the horizontal displacement of a root lateral from its parent branch can be derived from a combination of the genetic control of root morphogenesis, which is modified by soil environments and the geotropic tendencies of root growth. The growth trajectory of a root lateral is a product of elongation rate and curvature towards gravity. In the simple case of a homogeneous soil and a horizontal lateral root bud orientation, RSD increase with elongation rates and decrease with curvature rates. Plants that 'optimize' RSD, relative to water and ion absorption, are likely to synchronize lateral initiation soil conditions resulting with in 'optimal' growth trajectories of root tips.

Simulations of root function are improved when algorithms correspond to conceptual advances in analysis of root function. Gardner (1991) developed the concept of 'water uptake front', which corresponds to the root proliferation phase of development discussed here. Passioura (1985) derived a simplified root water uptake relation, lumping root distribution and hydraulic conductivity terms into time constant describing exponential decline in soil water depletion. Soil structural heterogeneities and corresponding root clusters can alter the time constant for root water uptake by an order of magnitude (Passioura 1991).

structure, and associated soil water depletion by analysis of MR techniques can be used to evaluate these relations, leading to optimization of soil-plant interactions.



Figure 2.10 Distribution of maize root separation distances (RSD) in a Spinks sand, computed from maize root distributions observed at anthesis growth state (day 217) for 1991 water deficit during the vegetative phase. RSD computed as $2*(\pi \cdot RN)^{-0.5}$, assuming uniform root distribution within 0.05 x 0.05 m cells in the soil profile.

CHAPTER 3

REMOTE SENSING OF ROOT FUNCTION

INTRODUCTION

Applications of root functions to management systems are constrained by our knowledge of heterogenous root distributions. Spatial and temporal variation in root networks restrict many inferences of root function gained by destructive root sampling methods. In situ and simultaneous analysis of root distribution and function can improve our understanding of soil-plant interactions.

Root networks function as sorptive sinks for water and nutrients, regulate plant water use, communicate with shoots, and may contribute to growth optimization. Soil carbon dioxide (CO₂) evolution is related to root growth and maintenance respiration and to microbial decomposition of organic carbon (Hall et al., 1990). Root respiration can amount to 40% of assimilate partitioned to roots (Martin, 1987). account for significant and errors in micrometerological estimates of photosynthesis. Physical models of root function frequently assume uniform root diameter and inter-root distances, though these parameters are log-normally distributed (Tardieu, 1988b; Logsdon and Allmaras, 1991). Non-uniform distributions of roots, water,

and nutrients violate assumptions required for models of radial transport of water and ions to single roots (Passioura, 1991; Luxmore and Stolzy, 1987).

Simultaneous, in situ, and repeated measurements of root distribution and function are necessary to quantify the effects of root morphology on root function. Minirhizotron imaging technology permits cost-effective, non-(MR) destructive, repeated field measurements of root and soil MR morphology (Upchurch and Ritchie, 1983). root observations are systematically related to conventional, destructive measurements of root length density for soil depths below 15 cm when access tube orientation is greater than 45⁰ relative to vertical (Upchurch and Taylor, 1990). Quantifying the relation of MR root observations to root function can strengthen field analysis of soil-plant interactions, especially when coordinated with measurements of additional parameters.

We hypothesize that biophysical models of root function can relate soil water depletion and CO₂ partial pressure distributions derived gradients to root from root intersections with MR tubes. Water uptake is a critical root function that is readily determined by neutron thermalization when water infiltration and redistribution are absent. Carbon dioxide source strength within the soil profile can be derived from $[CO_2]$ and soil water (Θ_v) distributions by the flux gradient method (de Jong et al., 19745; Campbell, 1985). This study was conducted to

determine the functional relation of MR root observations, neutron probe estimates of soil water and microtube gas sampling of soil CO_2 with sink strength for water and source strength for CO_2 .

METHODS AND MATERIALS

Crop culture

Maize (Zea mays, L. hybrid Pioneer 3573) grown in a 1.4 x 1.4 x 1.8 m non-weighing lysimeter (Figure 3.1) under a rain shelter was subjected to water deficits during vegetative growth in 1990 and during vegetative and reproductive growth in 1991. A Spinks sand (Sandy, mixed, mesic Psammentic Hapludalfs) was packed into the lysimeter and the associated 4.6 x 6.2 m field plot. The bulk density and corresponding depth intervals of soil layers are 1.3 Mg m^{-3} , 0.0 to 0.25 m; 1.27 Mg m^{-3} , 0.25 to 0.8 m; 1.46 Mg m^{-3} , 0.8 to 1.4 m; 1.49 Mg m^{-3} , 1.4 to 1.8 m. Crop culture is summarized in Table 3.1 and water supply is illustrated in Figure 3.3B.

Lysimeter Instrumentation

Polybutyrate tubes $(0.05 \times 1.4 \text{ m})$ were installed perpendicular to crop rows, parallel to the soil surface, with upper surfaces at depths of 0.50, 0.72, 0.90, 1.07, 1.27, 1.43, and 1.60 m. Duplicate MR tubes at each depth provided access for recording root intersections at soiltube interfaces with a microvideo camera (Ferguson and Table 3.1. Maize cultural practices for lysimeter in rain
shelter containing a Spinks sand at the Kellogg Biological
Station.Parameter19901991

	2330	2002
Planting Date (Day of year)	144	156
Emergence Date (Day of year)	152	163
Plant Population (plants m^{-2})	7.14	9.18
Nitrogen (g N m ⁻²)	20.0	12.0
Phosphorus (g $P m^{-2}$)	18.0	6.0
Potassium (g K m ⁻²)	6.0	6.0

Table 3.2 Day of year for Maize phenologic development for lysimeter in rain shelter containing Spinks sand at Kellogg Biological Station

 Phenological stage	1990	1991
Emergence	152	156
Eight leaf	191	194
Anthesis	212	217
Grain fill	230	238

Smucker, 1989) and sensing soil water with neutron probe (Gardner, 1986). The horizontal minirhizotron (MR) tubes were offset by 0.15 m such that a minimum of 0.3 m separated vertically adjacent MR tubes. Aluminum access tubes installed vertically in the crop row and furrow provided additional access for neutron probe determinations of soil water in 1990. Paired stainless steel rods installed vertically to 0.15 and 0.3 m soil depths served as parallel wave guides for determination of soil water content by time domain reflectometry (TDR, Topp, 1986) in 1991. Teflon capillary tubing, 0.5 mm dia. and 0.3, 0.6, 0.9, and 1.2 m in length, were fitted with septa and attached to the MR access tubes, providing access to the soil atmosphere in the regions visible by the MR tubes and microvideo camera. Replicate soil atmosphere microtubes were also installed vertically to depths of 0.03, 0.08, 0.15 and 0.3 m at positions 0.3, 0.6, 0.9 and 1.2 m from the east wall of the lysimeter. A weather data system (LI-1200S, LI-COR, PO Box 4425, Lincoln, NE 68504), located within 20 m of the lysimeter, recorded daily global radiation, maximum and minimum temperature, and precipitation.

Evaporative Demand

Potential evaporative demand (E_0) is computed daily by a modified Priestly-Taylor equation (Ritchie, 1985) as a function of global radiation (R_g) , daily ambient temperature extremes (T_{max}, T_{min}) , leaf area index (LAI) and soil



Figure 3.1 Instrumentation for repeated measurements of root distributions, soil water, and soil atmosphere in a non-weighing lysimeter under an irrigated rain shelter.

albedo. Mean E_O corresponding to soil water sampling intervals is computed from daily E_O .

Daily radiation, used in computation of E_0 , is adjusted for extended periods of rain shelter closure, when required for maintenance. The adjustment procedure is based on the assumption that diurnal radiation is distributed over a 14 h period as a sine function of daylight hours,

$$R_n' = R_n \int sine 2*pi(t-5)/28 dt$$
 [3.1]

where R_n ' is adjusted net radiation, R_n is net radiation, t is time of day (EST), sunrise occurs at 05:00 EST and sunset occurs at 19:00 EST. Integrating and evaluating at time of opening (t_o) and closure (t_c) gives the equation

$$Rn'= Rn*[(\cos 2*pi(t_0-5)/28) - (\cos 2*pi(t_c-5)/28)] [3.2]$$

Potential evaporative demand computed from weather data is used to verify the accuracy of evapotranspiration determined by the soil water balance method.

Crop development

Canopy structure was determined for three representative plants from each of two rows. Date of leaf maturation and senescence, mature leaf length and width, height to top mature ligule, and reproductive development phases are used to quantify green leaf area (GLA). Green leaf area is computed as a time (t) dependent function for each plant

$$GLA(t) = \sum_{i=1}^{m} L_{i} \times W_{i} \times 0.75 \qquad [3.3]$$

where L_i and W_i are the length and width of the "ith" leaf, m is the top mature leaf number, and s refers to the top senescent leaf number. Confidence intervals (Steel and Torrie, 1980) about the canopy green leaf area index (GLAI(t)) and height to top mature ligule (H(t)) are plant populations. from GLA(t) and Root computed intersections with MR tubes were recorded five times, by a Circon microvideo camera in 1990, and eight times, by a Bartz microvideo camera in 1991. Frame dimensions for the Circon camera are 12 x 18 mm, for the Bartz camera, 13.5 x 18 mm. The longer frame dimension is perpendicular to the MR tube. Active roots were manually identified by their hiqh light reflectance, opaque appearance, structural integrity and diameter exceeding 75 um. Senescent roots observed prior to crop establishment were excluded from root counts as were translucent roots and roots with low Root number (RN) values were determined by reflectance. computing root counts (N) per unit area (A) of the soil-MR tube interface, and were equated to root length density (RLD) by the following relation (Upchurch and Ritchie, 1983)

$$RLD = Nd/Ad$$
[3.4]

where d is the outer diameter of the MR tube. This relation assumes the mean length of roots intersecting the volume

occupied by the MR tube would be equal to the outer diameter of the MR tube, if the soil were not displaced by the MR tube (Upchurch and Ritchie, 1983).

The rooting front, e.g. initial root arrival at a given depth, is determined by reduction of stored soil water at rates exceeding 0.05 mm day⁻¹ for a 0.15 m soil layer, or by the initial root observation at the soil-MR tube interface. Root proliferation (R_p) during a sampling interval is computed for each MR tube as the rate of change in RN with respect to time

$$R_{\rm p} = dRN/dt \qquad [3.5]$$

Vertical distributions of mean root intersections observed for each horizontal MR tube are analyzed as a logrithmic function of soil depth

$$RN_z = a + b*log(z)$$
 [3.6]

where z is soil depth, a and b are empirical coefficients. This relation reflects the exponential distribution of roots that results from branching patterns.

Root distribution, in the horizontal direction perpendicular to crop row, is interpolated among MR observations in the 0.5 to 1.7 m soil profile by a geostatistical model and a block 'krige' interpolation routine (GS+, Gamma Design, Box 201, Plainwell, MI 49080). Kriged values are computed as a weighted average of 16 nearest observations. The weighting function is based on the spatial structure of variance within the region of interest. Spatial structure is quantified by semivariograms, providing a theoretical basis for optimal interpolation among observation points, with a defined error structure (Warrick et al., 1986). Root distributions in 0.05 \times 0.05 m cells throughout a 1.3 \times 1.2 m region are interpolated from root intersections with MR tubes. Deviations from vertical trends were obtained for each observation along the MR tube by subtracting the trend value from the observed value. Spatial correlation in deviations from the vertical trends is quantified by semivariance analysis. A theoretical model, describing semivariance as a function of distance separating observations, is fit to the semivariogram data. Root length density values, corresponding to 0.05 \times 0.05 m blocks within the soil profile, are obtained by adding 'kriged' interpolated values, derived from detrended data, to the vertical trend, quantified by equation [3.6].

Soil water depletion and sink strength

Soil water distribution was determined by neutron thermalization at three to seven day intervals following initiation of water stress. The neutron probe was inserted in vertical tubes centered in the crop row and interrow in 1990 and in the horizontal MR tubes. Only the horizontal MR tubes were used for neutron thermalization detection in 1991. The ratio of counts observed at 0.15 m intervals, to standard counts is related to volumetric soil water content by a field calibration procedure (Gardner, 1986). The apparent dielectric constant, determined by TDR is related

to soil water by the Topp equation (Topp et al., 1982)

$$\Theta_v = -0.053 + 0.0282 * K_a - 0.0005 * K_a^2 + 0.0000043 * K_a^3 [3.7]$$

where $K_a = (ct/L)^2$, $t = (B-A)/(V_p*c)$, c is the propogation of an electromagnetic wave in free space (30 cm s⁻⁹), L is the distance the wave guides are extended into the soil. V_p is the experimentally determined propogation velocity of the cable. B is the distance of the reflected pulse from the pulse generator, taken as the tangent made by the zero and positive slopes traced in the waveform. A is the distance separating the pulse generator from the junction of the TDR cable and wave guides, taken as the point preceeding the large negative slope in the waveform. Spatial and analytic components of soil water variability are computed as the standard deviation of replicate observations at identical depths.

The drained upper limit (DUL) soil water content is determined by constant soil water distribution following saturation, when active roots are absent. The lower limit (LL) of water extractable by maize was determined after 73 days of water deficits when the soil water distribution became satic even though active roots were present. Soil water available to maize crop (AW) is computed by subtracting LL for a horizon from volumetric soil water content for that layer. The quantity of available water stored in a soil layer 'i' is the product of AW and layer thickness (D_i) . The quantity of available water stored in the rooted soil profile (SAW_r) is the sum of stored water in all soil layers within the rooting depth, where z_r is maximum depth of rooting, as determined by the rooting front.

$$saw_{r} = \sum_{i}^{i=z_{r}} saw_{i}$$

$$(3.8)$$

The quantity of available water stored below the active root zone (SAW_v) is the sum of stored water in all layers from the rooting depth to the lysimeter base (z_b) .

$$SAW_{v} = \sum_{i=z_{r}}^{i=z_{b}} SAW_{i}$$

$$(3.9)$$

Stored soil water depletion for layer 'i' (SWD_i) is computed as the change in stored water (dSW_i) per unit time (dt), and equated to root sink strength (r_W) when infiltration, drainage and soil water redistribution terms of the soil water balance equation are zero.

$$SWD_i = dSW_i/dt$$
 [3.10]

Mean daily total evaporation (Et_m) is computed as the sum of SWD_i for each layer. Analytic error and horizontal variability in SWD_i is computed as the standard deviation of four replicate TDR differences, or eight replicate neutron probe differences for each soil layer.

CO2 gradients and net CO2 flux

Samples of the soil atmosphere, collected after unidirectional vacuum flushing the dead space of the collection system three times, were stored in 1.0 ml syringes sealed by inserting needles in neoprene stoppers. The CO₂ partial pressure was determined within three hours of collection by a modified infrared gas analyzer (IRGA), using N₂ as a carrier gas (Schumacher and Smucker, 1985). The output signal of the Beckman Model 865 IRGA (Beckman Instruments, Fullerton, CA) was integrated by a Hewlett Packard 1040a instrument (Hewlett Packard, Dallas TX), and related to CO₂ partial pressure by calibration with a minimum of five external standards, prepared prior to each sampling period. The CO₂ partial pressure for each soil depth was computed as the mean of four samples, taken along each MR tube, at each depth. The standard deviation of four observations includes spatial variability in horizontal distribution of source strength and analytical error.

Carbon dioxide source strength $(r_{C}(i))$ and change in stored CO₂ (dCO₂/dt) for soil depth 'i' was computed from the mass balance of CO₂ at each sampling node.

$$r_{c}(i) - \theta_{a} dCO_{2}/dt = J_{c}(i) - J_{c}(i-1)$$
 [3.11]

computed from CO_2 flux ($J_C(i)$) above and below each sampling node, where Θ_{α} is air-filled porosity.

$$J_{c}(i) = \frac{D ([CO_{2}(i+1)] - [CO_{2}(i)]}{z(i+1) - z(i)}$$
[3.12]

where D is gas diffusivity; $[CO_2(i+1)]$ is the partial pressure of CO₂ at soil depth 'i+1'; $[CO_2(i)]$ is the partial

pressure of CO_2 at soil depth 'i'; and z(i+1) and z(i) are corresponding soil depths. Gas diffusivity is computed as an exponential function of air-filled porosity (Θ_g) (Campbell, 1985)

$$D = D_0 \cdot \epsilon(\Theta_q) \qquad [3.13]$$

where D_0 is the binary diffusion coefficient for CO_2 (1.39 x $10^{-5} \text{ m}^2 \text{ s}^{-1}$), $\epsilon(\theta_g) = 0.9 \star \theta_g^{2.3}$, $\theta_g = \epsilon - \theta_V$, and ϵ is total porosity.

Analysis of root function

Functional relations of root distributions to water sink strength and CO_2 source strength are determined by error analysis. Available water and RLD are related to soil water depletion by solving for root water uptake equation (r_w) as described by Gardner, (1960),

$$r_{w} = \frac{4\pi K(\Theta) (\Psi_{r} - \Psi_{g})}{\ln (c^{2}/r^{2})}$$
[3.14]

where $K(\theta)$ is unsaturated hydraulic conductivity, Ψ_r is root water potential, Ψ_8 is water potential of the bulk soil, c is the radius of a cylinder of soil from which water diffuses to the root, and r is root radius. Ritchie (1985) derived a simplified solution to the equation [3.14], assuming:

$$K(\Theta) = 10^{-5} \exp (62(\Theta_v - LL))$$

(r - s) = 21 cm water
 $c = (\pi RLD)^{-0.5}$
 $r = 0.2 mm$

substituting these relations into equation [3.14] yields

$$q_r = -$$

6.68 - ln RLD [3.15a]

$$\mathbf{r}_{w} = \mathrm{RLD} \cdot \mathbf{q}_{r}$$
 [3.15b]

where Θ_V is volumetric soil water content, and LL is the lower limit for available soil water. Deviation of predicted root water uptake (r_w) from observed soil water depletion (SWD) is computed by

Predictive Error =
$$\frac{1}{-\Sigma} \sqrt{(r_w - SWD)^2}$$
 [3.16]

Coefficients in Equation [3.14] are used as published.

RESULTS

Canopy and root development, and evaporation

Canopy height proceeded at similar rates in 1990 and 1991 (Figure 3.2), though planting dates differed by 12 days. Mature leaf areas differed however, as the average leaf area from day 180 to 220 was 40% greater during the 1991 growing season. Greater development of leaf areas during the 1991 season appeared to be due to a greater plant



Figure 3.2 Maize canopy development on a Spinks sand for water deficits during vegetative phase in 1990, (A) green ligule height. Maize canopy leaf index, (B) top area development for water deficit periods during vegetative and reproductive phases in 1991, (C) green leaf area index, (D) ligule height. top Dashed lines are 90% confidence intervals.

population (Table 3.1), and greater leaf dimensions. Rapid leaf senescence after day 220 in 1991 (Figure 3.2C) may be attributed to the prolonged water deficits occurring (Aiken, 1992, pp. 36-41) during this period of plant growth. Available water stored in the root zone was less than 50% of potential water holding capacity after day 199. Soil water depletion coincided with canopy loss of turgor observed on day 199 and leaf rolling observed on days 213 and 217.

Root accumulations during 1991 are evident above soil horizon interfaces at 0.72 and 1.27 m depths (Figure 3.3A). Discontinuities in soil texture and associated hydruaulic properties can promote root proliferation when water and nutrients accumulate above horizon interfaces (Smucker and Roberson (1989). Root accumulations at 1.6 m are attributed to the artificial boundary effects of the lysimeter base, which retained water above the drained upper limit.

Root proliferation also corresponded with water deficits and with the ratio of observed and predicted daily evaporation (Figure 3.4). An exponential decline in soil water is apparent in the upper 0.5 m prior to loss of leaf turgor observed on day 199. This evidence of deficient water supply to the canopy coincided with a green leaf area index of 2 m² m⁻² (Figure 3.2C), RN values of less than 0.1 cm cm⁻³ (Figure 3.3A) which were restricted to the upper 1.3 m of soil, and less than 0.03 cm³ cm⁻³ of available water in the upper 0.75 m soil layers (Figure 3.3B). Deficient water supply to canopy is confirmed by mean daily evaporation



Seasonal trends in maize root-soil water Figure 3.3 on a Spinks sand in 1991 for water deficit interactions during vegetative and reproductive phases: (A) root soil development **(B)** available water (C) soil water depletion (D) predictive accuracy of a cylindrical root water uptake model. Note shift in axes for available water (B), required to display seasonal trends in soil water depletion.

(Et_m) values, computed from soil water depletion over sampling intervals, which are 38% lower than mean daily evaporation potential (E_0), computed from weather data by a modified Priestly-Taylor equation over the 196-205 day interval (Figure 3.4). Subsequent root proliferation throughout the 0.5 to 1.65 m profile (Aiken, 1992, pp. 36-41) illustrates compensatory growth, increasing the water supply capacity of the root network.

The pattern of deficient plant water supply and subsequent root proliferation recured, with leaf rolling observed on day 213 and 217. Mean daily evaporation was 57% lower than potential evaporation during the 213-217 day interval (Figure 3.4) and roots proliferated at 0.5, 1.27, and 1.6 m depths (Aiken, 1992, pp. 36-41). These results indicate transient deficits in plant water supply can result from localized water depletion in rooted soil, though roots are growing into wet soil. Thus, detecting the vertical rooting front failed as an index of plant-available water, for 9 cm of "available" water were stored in "rooted" soil (Aiken, 1992, p. 40) when the ratio of Et_m/E_0 fell below 0.45.

Mean daily evaporation (Et_m) exceeded potential evaporation (E_0) during the 217-224 day interval (Figure 3.4). This result is attributed to biased estimates of green leaf area index (GLAI, Figure 3.2C), attaining maximum values at this period. If GLAI was 2.5 m² m⁻² rather than the reported 5 m² m⁻², E₀ would increase by 56% due to



Figure 3.4 The ratio of mean daily evapotranspiration (ET_m) to mean daily potential evaporation (E_0) is illustrated for maize subject to water deficits during vegetative and reproductive phases in 1991. ET_m was determined by soil water depletion (N = 56 observations for each of two similar profiles). E_0 is daily potential evaporation, computed from a modified Priestly-Taylor equation. LCI and UCI are 90% lower and upper confidence intervals for daily soil water depletion, integrated over sampling intervals.

effects of decreased albedo. The magnitude of this probable bias corresponds to the magnitude that observed evaporation (E_m) exceeds predicted evaporation (E_0) (Figure 3.4). Thus, conclusions that observed evaporation exceeded atmospheric potential evaporation is probably invalid as potential evaporation is likely underestimated due to biased estimates of soil plus canopy albedo.

Soil water depletion

Derivations of the single root water uptake model are frequently used to solve the uniform cylindrical flow of water to a single root (Gardner, 1960; Ritchie, 1985) These formulae are used to relate soil water depletion to RLD and AW, observed at seasonal and spatial scales. Soil water depletion rates, observed at three to seven day intervals (SWD_0) , are compared with root water uptake, predicted by equation [3.15a and b] (SWD_p) . Predicted values are based on root intersections with horizontal MR tubes, and soil water detected by neutron thermalization in the same MR tubes.

Measured soil water depletion rates decreased as a linear function of soil depths, from 0.75 to 1.45 m prior to anthesis in 1990 (Figure 3.5C and D). Predicted soil water depletion tended to increase with soil depth, reflecting vertical trends in the profile distribution of soil water and roots (Figure 3.5A and B). Predictive error was nearly equivalent to the magnitude of soil water depletion for successive sampling intervals. These results suggest a



Figure 3.5 Comparison of soil water depletion, observed by neutron thermalization (SWD_0) , with depletion due to root water uptake predicted by a simplified solution to a cylindrical model of root water uptake (SWD_p). Observations under maize in a Spinks sand for water deficits during vegetative stage in 1990. (A) Soil profile distribution of available water, (B) Soil profile distributions of root number, (C) Soil water depletion, predicted and observed for 205-208, (D) Soil water depletion, predicted days and observed for days 208-214. Upper and lower 90% confidence limits are computed for N=8 observations.

systematic bias in equation [3.15a and b]. Biases in estimates of root water uptake could result from systematic errors in measure of available water (AW) and root length density (RLD, equated to RN by equation [3.4]). Systemic bias in AW determination is unlikely as the neutron thermization conditions were identical at all depths, and neutron probe calibration results indicate linear response of the range observed (Gardner, 1986).

However, MR intersections may underestimate RLD during initial root extension into soil layers, as the rooting front is detected by soil water depletion prior to root intersection (Aiken, 1992, p. 36). But underestimating RLD would result in underestimating SWD, while the contrary was observed (Figure 3.5C and D). Thus, systematic bias in measurement of AW is unlikely, and effects of a likely biased in estimates of RLD are opposite in direction to the bias in predicted SWD.

Systematic bias may result from invalid assumptions of soil and plant hydraulic properties. Differences in radial conductivity in suberized and unsuberized dermal layers of conductive and sorptive regions of roots (Russell, 1977) are neglected in equations [3.15a and b], and could account for biased predictions. But consideration of differences in radial conductivities would tend to increase the bias in predicted SWD, for younger roots at greater soil depths are expected to have a higher proportion of sorptive regions than older roots higher in the soil profile. Soil

unsaturated hydraulic conductivity (K(Θ), equation [3.15a]) is sensitive to the value of the exponential coefficient, doubling in value with a 10% increase in the exponent when AW is 0.12 cm³ cm⁻³. But errors in the K(Θ) function can only account for the magnitude, not direction, of predictive error, for a smaller coefficient would still predict increasing water uptake for the high AW conditions observed at greater soil depths. Systematic bias in soil and root components of radial resistance to root water uptake fail to account for the direction of bias in predicted SWD.

The assumption of uniform hydraulic gradient between root and soil is valid only if root axial resistance to water flow and gradients in root xylem water potential are negligable. Experimental evidence (Yamauchi et al., in press; Hainsworth and Aylmore, 1989) contradicts this assumption. Axial resistance to water flow in roots would increase the hydraulic gradient required for water flow through xylem vessels. Thus, xylem water potential would be less negative with respect to rooting depth, with corresponding reductions in radial root-soil hydraulic gradients with respect to rooting depth. Depth-dependent effects of frictional resistance along xylem vessels accounted for water uptake patterns observed for cotton and soybean (Klepper et al., 1983). We attribute systematic bias in predicted water uptake to effects of axial resistance on radial root-soil hydraulic gradients that are not considered in equation [3.15a and b]. These effects

could be approximated by making the soil-root hydaulic gradient a linear declining function of soil depth.

Seasonal trends in predicted SWD (Figure 3.3D) and soil water depletion (Figure 3.3C) observed in 1991 confirm diagnosis of systematic bias observed in 1990 (Figure 3.5). More water was taken up from layers above 1.0 m than from lavers below this depth prior to depletion at day 200 (Figure 3.3C). This is attributed, in part, to the timing of root extension and proliferation into wet soil (Figure Recall, this coincides with visual evidence of 3.3A). deficient plant water supply, observed on days 199, 213 and (Aiken, 1992, pp. 36-39). In contrast to field 217 observations, predicted SWD underestimates the proportion of water uptake at more shallow depths and overestimates the proportion of uptake deeper in the soil profile. Thus, systematic bias in predictions of the vertical distribution of root water uptake persisted throughout an extended drying cycle for maize roots growing into wet soil.

Error in predicted root water uptake can be attributed to changes in RN during root proliferation phases, when they are not accounted for in equations [3.15a and b]. Robertson et al. (in press) determined that root water uptake during early phases of grain sorghum root proliferation was overestimated by an exponential decline model of soil water depletion, taken from Passioura (1983), that assumes constant RLD.

Cabon dioxide evolution

Seasonal trends in CO_2 evolution observed in 1990 are also related to root development (Figure 3.6A and 3.6C). Net CO_2 flux, including source strength and transient storage effects, was computed from flux gradient data using Equation [3.11]; and is concentrated in the upper 0.5 m of soil, where root observations by MR were restricted by the deeper locations of MR tubes (Figure 3.1). Carbon dioxide accumulation in the 0.5 to 0.9 m layer at day 195 corresponds with increased source strength (Figure 3.6B) and root proliferation (Figure 3.6C) at this depth and time. Accumulation of CO_2 below 0.75 m to 1.6 m during day 210-220 corresponds to a shift in the proliferation of roots to these soil layers. A flush of respiration on day 220 (Figure 3.6B) coincided with an initial wetting event when the water deficit period was ended by irrigation.

Seasonal trends in CO_2 evolution observed in 1991, Figure 3.7, indicate similar increasing CO_2 gradients with respect to soil depth, as observed in 1990, Figure 3.6; though CO_2 accumulations below 0.7 m were twice that observed in 1990 (Figure 3.6A). The steepest gradient in the partial pressure of CO_2 , Figure 3.7A, occurred in the 0.5 to 0.7 m soil layer in 1991, but between 0.15 and 0.5 m layers in 1990. Relatively greater CO_2 accumulations and a shift in maximal CO_2 gradients in 1991 to lower soil depths, relative to 1990 indicate greater root plus soil respiration at lower soil depths. This difference is attributed to



Figure 3.6 Seasonal trends in net CO_2 flux for water deficit during the vegetative phase for maize on a Spinks sand in 1990 (A) seasonal trends in the soil profile CO_2 gradients, (B) seasonal trends in soil plus root CO_2 source strength, (C) seasonal trends in root distribution.



Figure 3.7 Seasonal trends in net CO_2 flux for water deficit during the vegetative and reproductive phases for maize on a Spinks sand in 1991 (A) seasonal trends in the soil profile CO_2 gradients, (B) seasonal trends in soil plus root CO_2 source strength, (C) seasonal trends in root distribution.
greater soil microbial decomposition of senescent roots remaining from the previous growing season. Decomposition was delayed in 1991, but not in 1990, by dry soil conditions the previous fall and winter. Reduced CO_2 accumulations, observed prior to day 217 and after day 260, coincide with reduced soil water depletion (Figure 3.3C). Presumably, reduced transpiration corresponds to reduced photosynthesis, consistent with reports of a close linkage of root respiration with canopy assimilation (Hall et al., 1990; Martin, 1987).

The non-linearity of CO_2 gradients and corresponding non-linear distributions of CO_2 flux indicate assumptions of steady state CO_2 flux conditions may be invalid. This inference follows from inspection of the steady state condition, derived from the mass balance for CO_2 (equation 3.11):

$$dCO_2 \quad dJ_C \Theta_g ---- = ---- + r_c = 0$$
 [3.16]

Under steady state conditions, gradients in CO_2 flux can only be attributed to r_c , the net reactions involving CO_2 (primarily generation by respiration). The persistent large negative values for net CO_2 flux at 0.08 to 0.15 m depths are not likely to result from soil reaction with CO_2 or plant root uptake of CO_2 . More likely, negative net flux reflects CO_2 accumulation in these layers as CO_2 respired by roots and soil organisms in lower soil layers diffuse through soil pores towards the atmospheric sink. Thus, regions of CO_2 source strength; occurring near the soil surface, at 0.75 m and 1.5 m; are bounded by regions of net CO_2 accumulation at time of sampling (just prior to solar noon).

DISCUSSION

A simplified solution to the single root water uptake model results in systemtic, depth-dependent bias in predicted root water uptake. Failure to consider depth dependent gradients in root xylem potential, arising from root axial resistance to flow, most likely accounts for the positive bias, with respect to soil depth, in predicted root water uptake. Vertical gradients in soil water depletion are consistent with nonuniform uptake observed by Hainsworth and Aylmore (1989); and with nonlinearities in root water flux relations predicted by Dalton et al. (1975).

Spatial and temporal variations in soil and root hydraulic properties can contribute to errors in predicting the quantity and distribution of root water uptake in the soil profile For example, water potential gradients between roots and the soil are expected to fluctuate as stomatal resistance adjusts to fluctuating evaporative demand, radiative heat loading, etc. Soil dessication can reduce the root-soil water contact, and alter root radial resistance to water flow due to senescence or suberization of root tissue. These effects are not considered, however, in predicted root water uptake (equation [3.15]). Horizontal gradients in root distributions, and clustered root distributions are expected to result in corresponding gradients in water and nutrient uptake (Aiken, 1992 p. 39). Failure to account for these gradients can reduce sensitivity of crop growth models to transient plant water deficits that can alter transpiration, assimilation, and C allocation patterns. Horizontal gradients in root distributions, affecting soil water uptake and transport are particularly relevant to ridge and no till systems where repeated root exploration of the same soil volumes beneath crop rows accelerates the depletion of immobile nutrients; and enhances the innoculum potential for root pathogens.

Modification of root water uptake models should take into account root axial resistance to water flow, spatial root geometries, seasonal changes in root hydraulic properties, horizontal gradients in the various soil conditions and related transport parameters. The regularities in root system development implicit in Poff, 1990), thermotropism (Fortin and multi-order branching (Rose, 1983), and phasic development (Klepper, 1987; Ritchie and NeSmith, 1991) suggest opportunities for predicting root system development. Integrating these regularities in root development with concepts of compensatory growth (Russell, 1977) suggests the need for a renewed direction for analysis of soil stress effects on plant growth and development (Luxmore and Stolzy, 1987).

CHAPTER 4

ROOT FUNCTION AND NITRATE LEACHING UNDER MAIZE

INTRODUCTION

Nitrate leaching represents a public health hazard and retention of an essential nutrient. the low Leaching losses are minimized when root uptake is synchronous with soil nitrate supply. Root uptake of N in the transpiration stream is an explicit sink in the conservation equation for solutes. Root effects on whole plant growth and development also modify N leaching potential by conditioning root and canopy architecture, and subsequent demand for water and N. Relating the effects of root system development and subsequent activity to nitrate leaching requires knowledge of factors regulating soil $[NO_3]$ and water flux, which determine N leaching rates at the lower boundary of rooted soil.

Simulations of the soil N balance, including leaching losses, are hampered by inadequate knowledge of the distribution and activity of plant root systems. Knowledge of root responses to environmental factors are based on young plants cultured under controlled environments (Klepper et al. 1983). Simulations of root geometries in field conditions typically assume horizontal homogeneity and prescribed vertical distributions, subject to environmental constraints. Accurate specification of the functional

equilibria between root and shoot activities and growth (Brown and Scott, 1984) may improve simulation sensitivity to root function.

Numerical simulations of complex systems are verified when solutions conform to fundamental physical laws, e.g. conservation of energy and matter, and accurately represent the conceptual model of system structure (Manetsch and Park, 1987). Simulations are validated when system state and output parameters are accurately predicted. Simulation of root effects on N leaching can be validated by evaluating the deviation of predicted water, C, and N distributions from those observed under field conditions.

This study was conducted to determine the sensitivity of N leaching predictions to errors within root system distributions, as simulated by CERES-Maize (Jones et al., 1986). We hypothesize that the predictive accuracy of simulated N leaching, by CERES-Maize, is sensitive to errors in simulated root morphogenesis. Model predictions of soil and plant C, water, and N state and output parameters are compared with field observations of lysimeters with conventional or no-till crop cultures.

METHODS AND MATERIALS

Crop culture

Maize (Zea mays, L. hybrid Pioneer 3704) was grown in duplicate 1.2 x 2.1 x 1.8 m field lysimeters under conventional till (CT) or no-till (NT) crop culture, with no

fertilizer additions in 1991. A previous corn crop, established in July, 1990 was followed by a rye crop, established in October, 1991. The rye was killed on day 131. 1991 at the vegetative stage with Round-up (0.06 L m-2 of 1:8 Round-up:water solution). The rye shoots were clipped and removed on day 135, 1991. Residual nitrate from application on day 212, 1990 was estimated to be 500 Kg N Ha-1 and greater. Moldboard plowing was simulated by spading the soil to a depth of 0.2 m on day 140, 1991. Three rows of corn were hand-planted in each lysimeter on day 140 which was concurrent with the associated field plots, Figure 4.1. Plants were thinned to a population of 8.33 plants m-2, seven plants per row. Nonuniform germination required thinning and transplanting in the lysimeters at the threeleaf stage for seven plants in NT6, two plants in NT9, and 15 plants in CT13. The canopy over the lysimeter was continuous with the field canopy in 1991, with the exception of a 1 m gap over each access chamber adjoining each lysimeter.

Lysimeter instrumentation

Lysimeters were installed and instrumentation was installed in early to mid 1990, as described in Figure 4.2 and Table 4.1. Methods used to determine the state of crop and soil parameters are described in later sections. Methods used to simulate weather effects on crop and soil interactions are described in the final section.



Figure 4.1 Diagram of field plots established at the Kellogg Biological Station in 1986 to investigate N supply and tillage effects on soil-plant interactions in lysimeters located in plots 2, 6, 9, and 13.



Figure 4.2 Instrumentation ports for non-destructive sampling of root distributions, soil water, soil solutes, and soil atmosphere above and below soil horizon interfaces in non-disturbed field lysimeters on a Kalamazoo loam soil.

Field lysimeters were installed in field plots established at the Kellogg Biological Station (KBS) in 1986 to investigate N supply and tillage effects on soil-plant interactions (Robertson and Smucker, 1988). The non-weighing lysimeters were located five meters from the boundary of the 27 x 40 m field plots by excavating around a 1.2 x 2.1 x A stainless steel lysimeter chamber was 1.8 m pedon. inserted over the nondisturbed portion of the excavation, and driven around the pedon. The lysimeter-pedon assemblage was inverted and a base and 0.43 m extension were welded onto the assemblage, and filled with sand from the soil parent material. A nylon screen separated a layer of peasized gravel which was covered by a stainless steel base sloped to the center drain (Figure 4.2). The lysimeter was uprighted and returned to the original field site. The surrounding soil was restored to the excavation site. Soil samples and mapping of horizon boundaries provided detailed information of soil physical and chemical properties for each lysimeter.

Instrumentation ports for the nondestructive sampling of root distributions, soil water content, soil solutes, and soil atmosphere were installed in clusters 0.02 m above and below soil horizon interfaces, directly below the center row. Polybutyrate minirhizotron (MR) tubes (0.06 x 1.2 m) parallel to the center crop row and the soil surface provided access for recording root intersections (Ferguson and Smucker, 1989) by a color microvideo camera (Bartz

Technology Co., 650 Aurora Ave. Santa Barbara, CA 93109). Teflon capillary tubing $(0.5 \text{ mm ID } \times 2 \text{ m})$, fitted with septa and taped to the MR access tubes provided access to the soil atmosphere at 0.25, 0.50, 0.75 and 1.00 m behind the lysimeter wall. Hypodermic needles

Table 4.1 Lysimeter horizons and NO_3 -N status on day 123, 1991 of Kalamazoo loam soil at Kellogg Biological Station. Rye biomass removed on day 135, 1991.

Soil layer	CT2	CT13	NT6	NT9
Ар	0-25	0-23	0-21	0-21
Е	-	24-30	21-30	21-30
Bt	25-53	30-64	30-56	30-48
2Bt2B	53-73	64-84	56-66	48-55
2Bt2C	-	-	66-83	-
2Bt3	-	-	83-107	55-78
3E\Bt	73-	84-	107-	78-
Residual N Kg N ha-1	1443	346	183	450
Rye Biomass Kg ha-1	4730	4440	4080	4760

(0.5 mm ID) or stainless steel capillary tubing (0.5 mm ID.), fitted with similar septa, were installed in the vertical direction in the topsoil with sampling depths at 0.03, 0.07 and 0.15 m. Paired 0.01 x 0.3 m stainless steel

rods served as parallel wave guides for time domain reflectrometry (TDR) determination of soil water (Topp et al., 1982). The TDR rods were oriented horizontally and parallel with crop row (Figure 4.2). The soil solution was sampled by suction lysimeters (Soil Moisture, P.O. Box 30025, Santa Barbara CA 93105) composed of ceramic cups (0.03 m OD) attached to 0.4 m cylinder and inserted 0.3 m into the soil. Each lysimeter drained at the base of the soil profile. Continuous drainage emptied into a 58 L collection vessel, enabling determination of instantaneous and cumulative outflows of water and corresponding samples of solute concentrations.

Weather

Daily global radiation (R_{α}) , precipitation (P), and temperature maxima (T_{max}) and minima (T_{min}) were recorded from day 154 through day 275 by a weather data system (LI-1200S, LI-COR, Lincoln, NE 68504) located within 200 m of the lysimeters. Daily quantity and duration of T_{max} , and T_{min} were also observed at a precipitation, National Weather Service (NWS) reporting station two Km west of the lysimeters. NWS weather data is combined with R_{α} data, recorded at the KBS Pond Lab, to characterize weather conditions at the lysimeters when on-site data were not available. Potential evaporative demand (E_{O}) is computed daily by a modified Priestly-Taylor equation (Ritchie, 1985) as a function of R_q , T_{max} , T_{min} , leaf area, and soil albedo.

Crop development

Canopy development was determined on 21 sampling dates for five plants within the population of each lysimeter. Date of leaf maturation and senescence, mature leaf length and width, height to top mature leaf ligule, and reproductive development phases were determined to quantify canopy structure. Green leaf area (GLA) was computed for each plant at each sampling period

$$GLA = \sum_{s}^{m} (L_{i} \times W_{i} \times 0.75)$$
 [4.1]

where L_i and W_i are the length and width of the "ith" leaf, 0.75 is a shape factor, m is the top mature leaf number, and s refers to the top senescent leaf number.

Confidence intervals (Steel and Torrie, 1980) about the canopy green leaf area index (GLAI) and height to top mature ligule (H) are computed from GLA and plant populations. Variable plant development required adjusting individual plant leaf area and stem height according to the relative frequency of small and large plants in the sampled and whole lysimeter populations. Plant height at day 200, determined for all plants in the lysimeter, served as the basis for adjusting the weights of individual plant measurements. The relative frequency of plants in six height classes, bounded by one or two standard deviations from the mean was determined for the population of plants in each lysimeter, and for plants selected for detailed sampling. Weighting factors for mean canopy leaf area and plant height are computed as

$$w_i = f_{pi}/f_{si} \qquad [4.2]$$

where w_i is the weighting factor for plants in the "ith" size class, f_{pi} is the frequency of plants in the lysimeter population (N=21) for the "ith" size class, f_{si} is the frequency of plants in the lysimeter sample population (N=5) for the "ith" size class. Weighted mean canopy leaf area is computed by

$$\Sigma w_{i} \sum_{s}^{m} GLA_{i}$$

$$GLAI = ----- \qquad [4.3]$$

$$\Sigma w_{i}$$

where w_i represents the sum of the relative frequency weighting factors, GLA_i represents the sum of mature green leaf area, m is the top mature leaf number, and s is the top senescent leaf number for the time of computation.

Root intersections with MR tubes were recorded five times by a microvideo camera in 1991. Frame dimensions are 13.5 x 18 mm, with the longer dimension perpendicular to the MR tube. Active roots were identified by high light reflectance, opaque appearance, structural integrity and diameters exceeding 75 um. Senescent roots, observed prior to crop establishment, were excluded from root counts as were translucent roots and roots with low reflectance. Root number values are determined by computing root counts (N) per unit area (A) of the soil-MR tube interface, and are equated to root length density (RLD) by the following relation, suggested by Upchurch and Ritchie (1983)

$$RLD = Nd/Ad \qquad [4.4]$$

where d is the MR tube outer diameter. This relation assumes the mean length of roots intersecting the volume occupied by the MR tube would be equal to the outer diameter of the MR tube, if the soil were not displaced by the MR tube (Upchurch and Ritchie, 1983). Root proliferation (Rp) during a sampling interval is computed for each MR tube as the rate of change in RN with respect to time (t)

$$Rp = RN/t \qquad [4.5]$$

Vertical distributions of mean root intersections observed for each horizontal MR tube are analyzed as a logarithmic function of soil depth

$$RLD = a + b*log(z) \qquad [4.6]$$

where z is soil depth, a and b are empirical coefficients determined by the software CricketGraph (MacIntosh, Redmond WA 98073).

<u>Soil conditions</u>

Distributions of soil water content and CO₂ partial pressures were determined bi-weekly, from day 140 through day 275. Drainage and leachate [NO₃-N] determinations began on day 88, and continued each week for one year. Extraction of the soil solution, and subsequent analysis coincided with soil water and CO_2 sampling, but were discontinued when water failed to flow into individual suction lysimeters due to dehydration of adjacent soil.

Soil water content was determined at sampling ports by time domain reflectometry (TDR). TDR is based on the principle that an electromagnetic wave, transmitted along parallel wave guides, is damped in a systematic manner that is proportional to the surrounding dielectric field. As the dielectric constant is nearly 30 times greater than mineral soil constituents, TDR observations are highly correlated with volumetric soil water content. A Tektronix 1502C cable tester served as signal source and analyzer. The apparent dielectric constant, determined by TDR (Topp et al., 1982), is related to soil water content by

$$\emptyset_v = -0.053 + 0.0282 * K_a - 0.00055 * K_a^2 + 0.0000043 * K_a^3 [4.7]$$

$$K_a = (ct/L)^2$$
 [4.7a]

$$t = (B-A)/V_{p}*c)$$
 [4.7b]

Where "c" is the propagation velocity of an electromagnetic wave in free space (30 cm s⁻⁹). V_p is the experimentally determined propogation velocity of the cable. L is the length the wave guides extend into the soil. B is the distance that the reflected pulse is from the pulse generator, taken as the tangent made by the zero and positive slopes traced in the waveform. A is the distance that the connection between the TDR cable and the pair of wave guides are from the pulse generator, taken as the point before the large negative slope in the waveform.

Nitrate concentrations in the soil solution were sampled, at weekly frequencies, by applying -0.08 Mpa pressure to the suction lysimeter tubes, then harvesting the solution within two to seven days. Samples were stored at -20 CO within 12 h of collection. Leachate was collected directly from the drainage tube and from the collection vessel. The collection vessel was emptied each week, after sampling. Samples were stored at 4 C^o or -20 C^o. Drainage rates were determined by volume outflow at time of collection and cumulative outflow during the weeklv interval. Drainage flux (D) is computed from volume outflow (V) as

$$D = V/At$$
 [4.8]

where A is area of the lysimeter (2.88 m²), and t is time elapsed from last observation. Cumulative drainage (CumD) is computed as the sum of weekly outflow (V) per unit lysimeter area (A)

$$CumD = (V/A) \qquad [4.9]$$

Nitrate concentrations of soil solution and leacheate were determined colorimetrically (Lachat Quikchem, Milwaukee, WI 53218). Soil [NO3-N] was computed from solution [NO3-N], volumetric soil water content (Øv), and soil bulk density (BD)

Soil
$$[NO_3-N] = ([Solution NO_3-N] \cdot \Theta_v)/BD)$$
 [4.10]

The quantity of NO3-N stored in a soil horizon (NO3-N(h) is computed assuming a linear relation between upper and lower boundaries

$$Soil[NO_3-N]_u + Soil[NO_3-N(soil)]_1$$

NO3-N(h)=-----(Z_u-Z₁)*BD [4.11]
2

where Z_u is depth of the upper boundary and Z_1 is depth of the lower boundary of each horizon. Cumulative NO_3-N leached (CumN₁) is computed from drainage flux (D) and leachate [NO_3-N]

$$CumN_1 = (D*t*leacheate[NO_3-N]$$
 [4.12]

Samples of the soil atmosphere were collected after flushing the dead space of the collection system three times, and stored in 1.0 ml syringes sealed by inserting needles in neoprene stoppers. The CO_2 partial pressure was determined within three hours of collection by infrared gas analysis (IRGA), using N2 as a carrier gas (Schumacher and Smucker, 1985). The output signal of the Beckman Model 865 IRGA (Fullerton, CA 92634) was integrated by a Hewlett Packard 1040a, and related to CO_2 partial pressure by calibration with a minimum of five external standards, prepared prior to each sampling period. The CO_2 partial pressure for each soil depth is computed as the mean of four samples at each depth. Spatial variability in horizontal distributions of CO_2 source strength and analytic error is computed as the standard deviation of four observations. Soil temperatures at 0.15 and 2 m depths were determined concurrent with gas sampling, between 10:00 and 15:00 h.

Common Scenario Analysis

Common scenario analysis compares values predicted by alternative configurations of the simulation system qiven identical input conditions (Manetsch and Park, 1987). Interactions in the soil-plant-atmosphere-continuum are simulated by CERES-Maize v2.1; a functional model oriented to support global crop management decisions (Jones et al., 1986). Simulation performance is evaluated by comparing the deviation of simulated values from field observations for variables describing the state of the system. Deficiencies in simulation structure are diagnosed by the time trend and magnitude of deviation for predicted and observed values. State parameters evaluated for the field lysimeters include canopy leaf area, distribution of roots, soil water, soil N, and flux of water and N in leachate.

Simulations of soil-plant interactions also provide a basis for quantifying the relative importance of soil or plant factors as determinants of system behavior. Specifically, the relation of simulated root water and N uptake to nitrate leaching is quantified by modifying the standard root development module of CERES-Maize and

evaluating differences in system behavior. **CERES-Maize** allocates a growth-phase dependent fraction of assimilate to root growth within rooted soil according to depth-dependent weighting factors. Simulated root growth typically reaches a maximal root length density value throughout the rooted soil profile during the growing season. Maximum root length density (RLD_{max}) is normally 5.0 cm cm⁻³ for Ceres-Maize. The altered version of CERES-Maize simply reduces RLDmax to 2.0 cm cm⁻³, a value consistent with observed MR root intersections (Figure 4.5). Reducing RLD_{max} increases the simulated distribution of distances separating roots and is expected to modify simulated water and solute uptake, which are partially dependent on RLD. Sensitivity of simulated system behavior is indicated by altered state and output variables.

Predictions of nitrate leaching, associated with precipitation and irrigation, can be biased by inaccurate predictions of infiltration. CERES-Maize uses а proportionate loss approach to partition rainfall into runoff and infiltration fractions. A runoff index or curve number (CN), derived from hydrologic studies of the Soil Conservation Service (SCS) is used as a nomograph to determine the proportion of rainfall that is lost to surface runoff. An alternative rainfall partitioning approach is based on rain intensity and the capacity of soil to take in water. The time-to-ponding (TTP) analysis derives from surface soil infiltration theory and sets a threshold for

maximum soil water intake. When rainfall intensity exceeds this threshold, excess precipitation ponds or runs off the soil surface.

Sensitivity of N leaching predictions to errors in partitioning rainfall into infiltration and runoff components was tested by common scenario analysis. Simulated state and output parameters are compared when infiltration fraction of rainfall is estimated by either proportionate loss, quantified by a SCS curve number (CN), or by time-to-ponding (TTP) threshold intake values. The relative deviation of predicted values from observed are compared for these alternative infiltration methods as well as the modification of RLDmax.

Simulations of soil-plant-atmosphere interactions require specification of system characteristics and boundary conditions. System parameters required by CERES-Maize include soil physical and chemical properties, and plant cultural practices (IBSNAT Technical Report 5, 1986). (Parameters corresponding to lysimeter conditions in 1991, and used in simulations are reported in Appendix A.) Soil layers, corresponding to A_p and B_t soil horizons, were simulated as homogeneous layers with thicknesses of 0.11 \pm 0.03 m; layers in the 3E/Bt horizon were assigned depth intervals of 0.23 \pm 0.05 m (Table 4.1).

Soil hydraulic characteristics, including saturated water content (SAT), drained upper limit (DUL), and lower limit (LL) were specified for each soil layer (Figure 4.3).



Figure 4.3 Initial volumetric soil water (SWC) profile on day 122, 1991, determined by TDR; lower limit to maize root water extraction (LL), determined by neutron thermalization; and drained upper limit (DUL), determined by TDR, for a Kalamazoo soil at the Kellogg Biological Station: (A) Notillage (NT6) or (B) conventional tillage (CT2).

The drained upper limit (DUL) is the soil water content when drainage after saturation approaches zero. DUL for soil horizons of each lysimeter were determined by field observations of soil water content on day 318, when less than one mm of precipitation was recorded in the previous eight days, but 194 mm of rainfall occurred following crop The lower limit (LL) to maize root water senescence. by determined neutron thermalization extraction was (Gardner, 1986) for horizons of a similar soil profile of Kalamazaoo loam after 75 days of water deficit applied to maize (R. Carlesso, personal communication). DUL and LL values obtained for horizon boundaries were assumed homogeneous for a soil layer. Values assigned to layers between horizon boundaries were interpolated as a linear function of depth with the horizon. Coefficients describing surface water runoff (CN) and soil water drainage (SWCON) were obtained from the Kalamazoo loam soil description and guidelines for CERES simulations (Ritchie and Crum, 1989).

Time-to-ponding was simulated based on a soil water intake threshold of 3 mm h-1 for CT and 20 mm h-1 for NT. These values correspond to field data reported by Chou (1990), with the assumption that surface crusting reduces infiltration of CT soil by a factor of five. Rainfall intensity was computed assuming constant intensity for the duration noted by the NWS weather observer at the Kellogg Biological Station. Initial water intake was not limited by uptake capacity, thus the initial 2 mm of rainfall was

partitioned to infiltration for CT; the initial 4 mm infiltrated for NT soil. Subsequent rain was considered infiltration when intensity was below the threshold level. Rainfall exceeding the threshold value was partitioned to runoff. The TTP approach partitioned 56% of seven rains (232 mm) to runoff for CT, with total infiltration of 343 mm; whereas 100% of rainfall was partitioned to infiltration for NT soils, with cumulative infiltration of 473 mm.

The initial state of soil water (Figure 4.3) and NO3-N (Figure 4.4) distributions that were simulated in lysimeter profiles correspond to field observations at each lysimeter, as reported in Table 4.2. Procedures used to interpolate among observations and extrapolate above observations are described in this section. Soil water and NO3-N values assigned to soil layers were interpolated from values observed at Bt horizon boundaries on day 123, assuming a linear distribution of SWC and solution [NO3-N] with horizon boundaries. Soil nitrate in layers of the Ap horizon were assigned minimal values of 0.01 mg N Kg-1 soil (the smallest value which initiates CERES-Maize) for lysimeters with soil NO3-N depleted in the upper Bt horizon (CT13, NT6 and NT9). When soil NO3-N at the upper Bt horizon increased after tillage, the increase in soil NO3-N was attributed to leaching losses and equally partitioned to layers in the A_{p} horizon. Soil [NO3-N] distribution in the 3E\B_t horizon was interpolated assuming linear distribution between soil [NO3-N] observed at the upper boundary and leached [NO3-N]



Figure 4.4 Residual soil [NO₃-N] on day 122, 1991 for field lysimeters containing non-disturbed Kalamazoo loam soil at the Kellogg Biological Station (A) no-tillage and (B) conventional tillage. Actual depths of each soil horizon are listed in Table 4.1.

Table 4.2 Soil NO_3 -N distribution on day 122, 1991 in field lysimeters with non-disturbed Kalamzaoo soil at Kellogg Biological Station, as determined by suction lysimeters. Soil NO_3 -N status of A_p horizons estimated by leaching observed in Bt horizons after day 122.

	Soil	Soil	Soil	Bulk	Soil	Ho1	cizon
Horizon	Depth	Sol. N	Water	Density	Y N	Depth	n N
	m	µg/ml	cm3/cm3	Mg/m3	µg/g	m	Kg/ha
CT 2							
Ap	-	-	-	-	-	0.25	138.0
Btu	0.25	462.2	0.274	1.47	86.1	0.28	489.6
Bt_1^-	0.51	805.3	0.277	1.47	151.8		
2Btu	0.59	694.3	0.219	1.61	94.4	0.20	243.9
$2Bt_1$	0.76	612.7	0.150	1.61	57.1		
3E\Bt _u	0.82	550.9	0.138	1.70	44.7	1.30	593.4
3E\Bt ₁	2.03	109.0	0.14	1.70	9.0		
CT 13							
Ар	-		-	-	-	0.22	0.0
Btu	0.30	n.d.	0.320	1.52	0.0	0.34	54.0
Btl	0.60	104.4	0.304	1.52	20.9		
2Btu	0.68	129.3	0.265	1.59	21.6	0.22	67.7
$2Bt_1$	0.81	133.2	0.204	1.59	17.1		
	0.89	104.8	0.11	1.72	6.7	1.17	134.3
3E/BC1	2.03	102.7	0.11	1.7	6.8		
NT 6							
Ap	-	-	-	-	-	0.21	0.0
E	0.25	0.2	0.319	1.54	0.04	0.10	0.1
Btu	0.33	n.d.	0.332	1.58	0.00	0.26	0.1
Bt ₁	0.55	0.1	0.310	1.58	0.03		. – .
$2BT_{u}$	0.63	21.3	0.246	1.69	3.1	0.26	15.2
	0.74	39.4	0.164	1.69	3.8		
$2BL3_{u}$	0.02	4.9	0.101	1.69	0.5	0.24	2.6
2DC31 3F\B+	1 05	13 5	0.143	1.09	0.7	0 06	74 7
$3E BC_{u}$	2.03	13.5	0.120	17	1.U 9 1	0.90	/4./
27/261	2.03		0.14	1./	0.1		
NT 9							
Ар	-	-	-	-	-	0.21	0.0
E	0.25	0.3	0.317	1.54	0.06	0.09	0.1
Btu	0.33	n.d.	0.351	1.61	0.0	0.18	0.0
2Bt2	0.53	n.d.	0.219	1.61	0.0	0.07	0.0
$2BC3_{u}$	0.61	n.d.	0.178	1.65	0.0	0.13	0.0
	0.81	n.a.	0.128	1.05	0.0		
35\DCu 35\D+	U.89 2 A2	4.5	0.135	1 7	0.36	1.25	192.3
JE/BLJ	2.03	210.3	U.14	1./	52.1		

observed at the lower boundary. Soil water contents used to convert solution $[NO_3-N]$ to soil $[NO_3-N]$ by Equation [4.10] were the DUL for the upper and lower boundaries of the 3E\B, horizon. Residue biomass, after removing clipped rye, was assumed to be 5% of the shoot biomass. Root biomass of rye crop was computed from shoot biomass assuming a root:shoot ratio of 0.3. Root weighting factors, used to distribute root growth among layers within rooted soil, were derived from a second order linear function relating MR root observations to soil depth, equation [4.13a]. Coefficients were fit to MR root intersections observed in the field plots associated with the lysimeters at the study site (Figure 4.5, Robertson and Smucker, 1988). Root distributions observed at anthesis in 1986, a dry year, and in 1987, a wet year were pooled for analysis. Fertilizer treatments corresponding to residual N distributions in the lysimeter were used. Thus root distributions for fertilized plots were used to characterize weighting factors for CT lysimeters, and non-fertilized plots for NT lysimeters. The weighting factor (wri) assigned to each "ith" layer was the fraction of RLD(z) for the ith layer with maximum RLD (RLDmax) observed at the surface layer

$$RLD(z) = B_0 + B_1 z + B_2 z^2$$
 [4.13a]

RLD(z) wri = ----- [4.13b] RLDmax



Figure 4.5 Root distributions in field plots associated with non-disturbed lysimeters containing Kalamazoo loam soil at Kellogg Biological Station, and corresponding to fertility status of the lysimeters in 1987 and 1988 (A) notillage (NT) with no fertilizer, (B) moldboard plow and disc tillage (CT) with historic fertilizer supply (Robertson and Smucker, 1989).

RESULTS

Crop development

Seasonal differences in maize canopy (Figure 4.6) development correspond with differences in initial soil nitrate, stand establishment, and soil water recharge, conditions which are described in subsequent sections. Leaf expansion was most rapid for CT 2, corresponding to high residual NO_3 -N levels. Canopy development in CT 13 was delayed relative to CT 2 due to poor emergence and subsequent transplanting of 70% of the lysimeter stand. Reduced green leaf area for both NT lysimeters is attributed to soil N depletion by the prior rye crop, and was particularly severe for NT 9 (Figure 4.10A and B). Trends in canopy development correspond to differences in maximum leaf area.

Simulated canopy development reflects the direction, but not magnitude of residual N effects on canopy development, Figure 4.6. Leaf area is overestimated for CT 2 and underestimated for NT 6 and NT 9. The lack of stand uniformity precludes model evaluation for CT 13 predictions, for CERES-Maize assumes uniform stand development. Reduced soil water recharge observed under CT lysimeters were not reflected in CERES-Maize simulation (see next section), hence water deficit effects on canopy development observed at CT 2 and CT 13 are not represented in simulation predictions. Canopy development for NT6 and NT9 were



Figure 4.6 Maize canopy development in non-disturbed field lysimeters subject to either no-tillage (A) green leaf area index, (B) top ligule height; or conventional tillage (C) green leaf area, (D) top ligule height. Solid lines are means of actual measurements, dashed lines represent 90% upper and lower confidence intervals.

similar to that of CT2 despite severe soil NO_3 -N depletion (Figure 4.6). This indicates crop growth responses to N deficiencies are underestimated in CERES-Maize, N supply from net mineralization of organic matter was underestimated by CERES-Maize, or both.

CERES-Maize predictions of canopy development, valid only for uniform stands, reflected the direction, but not magnitude of residual N effects, and did not reflect effects of soil water deficits, associated with tillage treatments. These effects were not modified by reducing maximum root length density from 5.0 to 2.0 cm cm⁻³, nor by estimating infiltration by time-to-ponding, rather than proportionate loss.

Carbon dioxide accumulation in soil layers reflect seasonal differences in respiratory source strength and in effective gas diffusivity among the lysimeters (Figure 4.7). Soil CO_2 partial pressures generally increased with depth, though accumulations in surface horizons coincided with rains (sampling dates 184, 189, 203, 203 243). Increased soil water contents decreased gas-filled porosity, reducing diffusion of gases through surface layers.

Mean seasonal CO_2 partial pressures at the $2B_t$ horizon (0.6 m) were higher for NT6 (0.025 atm) and NT9 (0.019 atm) lysimeters than for CT2 (0.012 atm) and CT13 (0.011 atm). These differences are likely due to lower gas diffusivity in NT soils, resulting from lower total porosity due to fewer macropores, and lower air-filled porosity due



Figure 4.7 Seasonal trends in vertical distribution of soil CO₂ partial pressures non-disturbed field in lysimeters soil loam Kellogg containing Kalamazoo at Biological subject to either no-tillage (A) NT6, (B) NT9; or Station, conventional tillage (C) CT 2, (D) CT 13.

to higher soil water contents. Differences in CO_2 source strength can be inferred more accurately from net soil CO_2 flux computations than from profile distributions.

<u>Soil water</u>

Variation in rainfall and radiation interacted with tillage and canopy effects to determine seasonal patterns in soil water. Soil water depletion persisted from canopy closure (day 212) through maturity (day 276) for both CT lysimeter, but not NT lysimeters (Figure 4.8). Available water in the upper B_t horizon averaged 0.084 for CT and 0.164 for NT during this interval.

Lower SWC under CT, relative to NT following canopy closure could be attributed to differences in tillage effects on crop water uptake. Delayed soil water depletion in CT 13 (Figure 4.8D) did correspond with delayed canopy development (Figure 4.6C). However, soil water deficits developed in CT 13, but not in NT 6 or NT9 (Figure 4.8A and B) despite similar values for green leaf area index (Figure 4.6A), a primary determinant of crop water uptake when soil water is not limiting. Greater root proliferation under CT with high fertility conditions (Robertson and Smucker, 1989) was observed in the A_p horizon of associated field plots, relative to NT with no supplemental N supply (Figure 4.5A and B). The distribution of root water uptake could be shifted to upper soil layers under CT, relative to NT.



Figure 4.8 Seasonal trends in soil water distribution in non-disturbed field lysimeters subject to either notillage (A) NT 6, (B) NT 9; or conventional tillage (C) CT 2, (D) CT 13.

Greater root water uptake in the A_p horizon for CT relative to NT could contribute to tillage effects on soil water depletion.

Inference of reduced soil water recharge in the upper layer of the B. horizon for CT is corroborated by field observations of surface soil dispersion and crusting-indicating reduced infiltration rates; evidence of rill erosion on CT lysimeters and field plots--indicating runoff; and early failure of suction lysimeters in the upper Bt of CT lysimeters horizons relative to NT lysimeters and field plots--indicating soil water depletion. We infer tillage runoff, surface reduced infiltration increased and restricted subsequent water flux into and below the root zone.

Differential infiltration due to preferential flow paths that can be associated with no-tillage (Kanwar, 1991), and to surface crusts developing under CT would be greater for rains of high intensity, exceeding water intake capacity of CT but not NT. Such an event occurred on day 182 when 51 mm were received within a six h period; and again on day 203 when 77 mm occurred in 9 h (Figure 4.9). It is likely these, and similar subsequent rains exceeded the water intake capacity of CT soils, restricting soil water recharge relative to NT.



Figure 4.9 The distribution of rain used to simulate soil-plant effects on NO_3 -N leaching in field lysimeter on a Kalamazoo loam soil at Kellogg Biological Station. Records obtained from National Weather Service reporting station two Km west of lysimeters (days 123-153); and from data logger located with 200 m of lysimeters (days 154-275). Time-toponding (TTP) estimates of infiltration under CT based on soil water intake rates.
Simulated soil water content (SWC) values are compared with field observations for the upper layer of the Bt horizon (0.25 m depth, the TDR measurement nearest to the soil surface). Soil water recharge was simulated by two The standard procedure in CERES-Maize different methods. relies on proportionate loss of rainfall to runoff; quantified by a curve number (CN) derived by the Soil Conservation Service for soil texture, drainage, and slope characteristics (Ritchie and Crum, 1989). An alternative method under development (personnal communication, J.T. Ritchie) is based on the time-to-ponding (TTP) analysis of infiltration; surface water flux conditions exceeding soil intake capacity are defined by nonlinear functions of soil hydraulic characteristics. Soil water was simulated by both method of computing infiltration and two root growth conditions: RLD_{max}, a parameter defining maximum root length density was assigned either the default value of 5.0 or 2.0 $cm cm^{-3}$. Thus, interacting effects of infiltration and RLD on predictive accuracy are evaluated.

Simulated SWC was generally higher than field observations for NT6 (Figure 4.10A). Virtually identical results were obtained for NT lysimeters when either curve number (CN) or time-to-ponding (TTP) methods were used to partition rainfall to infiltration, reflecting similarity in simulated infiltration rates. Restricting maximum RLD (RLDmax) to 2.0 cm cm⁻³ had no effect on simulated SWC.



Figure 4.10 Seasonal trends in predicted and observed soil water content (SWC) for upper layer of Bt horizon of Kalamazoo soil under (A) no-tillage (lysimeter NT 6), or (B) conventional tillage (lysimeter Kellogg the 2) at CT Station. Simulation runs Biological time-to-ponding used (TTP) or number (CN) methods of estimating curve infiltration and RLD_{max} values of 5.0 or 2.0 cm cm⁻³.

under CT lysimeters Soil water content was underestimated by CN and TTP methods from day 150 (crop emergence) through day 170 (Figure 4.10B). The TTP method of determining infiltration underestimated SWC after day 170. Soil water contents simulated by the TTP method were parallel to but lower than observed soil water. The TTP method results in reduced soil water recharge and increased surface runoff for precipitation events when rainfall intensity exceeds the soil intake capacity due to surface crusting. Restricting RLD_{max} to 2.0 cm cm⁻³ resulted in slightly higher SWC when simulated by the TTP method, but not the CN method after day 180 (Figure 4.10B). This result is consistent with the logic of total soil water depletion limited by evaporative demand at high SWC, but by root and soil interactions at low SWC.

The numerical value of SWC predicted by CN method was close to observed SWC for the period from 180 to 210 days,, though fluctuations in simulated SWC did not correspond to observed wetting and drying cycles after day 220. The time trend of SWC predicted by the TTP method of partitioning precipitation into runoff and infiltration fractions was nearly parallel to observed SWC. Accounting for surface barriers to infiltration under high rain intensities by the TTP method reduced the biased estimate of SWC for CT plots when surface crusts reduced soil water intake capacity. The TTP method offers potential to improve accuracy in simulated soil water dynamics.

Boil Nitrate

Residual soil nitrate differed among all soil profiles in both magnitude and distribution (Table 4.3, Figure 4.4). Uncertainty about the quantity of initial N application rates, on day 212, 1990, limit comparisons of tillage effects on NO3-N leaching to distributions within soil layers; though the quantity of NO3-N stored in soil horizons indicate initial application rates exceeded 400 to 1700 Kg N ha-1. The fraction of residual NO3-N retained in Ap and Bt horizons under CT was 0.61 (CT 2) and 0.49 (CT 13), but only 0.10 (NT 6) and 0.002 (NT 9) under NT. It is interesting to note that NO3-N accumulations occurred at the lower boundaries of the Bt and 2Bt horizons for the CT lysimeters (Figure 4.4). Characteristics of these horizons include clay accumulations, and textural changes at horizon Systematic differences on NO3-N retention by boundaries. surface horizons are associated with tillage treatments and may account for the reports of root accumulations at this horizon interface (Robertson and Smucker, 1989).

Seasonal trends in the soil NO_3 -N profile are depicted in Figure 4.11. Soil NO3-N was consistently lower for NT, when compared to CT, reflecting minimal retention by A_p and B_t horizons, leaching losses and subsequent uptake by rye and maize crops in the NT. Lack of residual NO3-N at maize planting (day 156) for NT 9 indicated plant N uptake was generally restricted by net N mineralization rates. An exception to this rule occurred from day 180 to 200, when



Figure 4.11 Seasonal trends in soil NO₃-N distributions in non-disturbed lysimeter profiles subjected to either no tillage (A) NT6, (B) NT9; or conventional tillage (C) CT2, (D) CT 13. Note difference in scale among figures.

soil NO3-N accumulated (Figure 4.11B), suggesting that net N mineralization exceeded crop uptake. Rapid depletion of soil N in NT6 (Figure 4.11A), during the interval of time between day 120 to 150 illustrates effective sequestering of mineral N by the rye crop. Data collected from NT 9 indicate similar trends during this period, but are incomplete due to equipment failure in the upper B_t suction lysimeter, and not presented.

Seasonal trends in soil NO3-N for CT lysimeters reflect historic and applied tillage modifications of soil water (Figure 4.8), with corresponding effects on solute transport and transformation processes. Residual soil [NO₃-N] on day 122 in CT 2 were very high, by agronomic stands, but moderate for CT 13 (Table 4.3, Figure 4.5B). Soil NO3-N in the upper B_t horizon of CT 2 increased by 60 Kg ha-1 within two weeks following tillage (day 141 Figures 4.11C, 4.12). The concentrations of NO3-N in A_p and B_t horizons indicate high application and retention rates of NO₃-N for this lysimeter. Soil NO3-N depletion in CT 13 from days 90 through 150 is attributed to rye uptake and leaching losses. Continued soil NO₃-N losses after day 180 corresponded with rapid maize crop vegetative growth after the eight leaf stage.

Simulated soil NO_3 -N for upper and lower boundaries of the B_t horizon are compared with observations at lysimeter CT2 (Figure 4.12) where initial concentrations were 86 mg N Kg⁻¹ (upper B_t) and 152 mg N Kg⁻¹ (lower B_t) Table 2.2.

Simulated soil NO_3 -N for upper and lower boundaries of the B_t horizon are compared with observations at lysimeter CT2 (Figure 4.12) where initial concentrations were 86 mg N Kg-1 (upper B_t) and 152 mg N Kg-1 (lower B_t) Table 2.2. Increased [NO₃-N] in the upper B_t after day 142 followed soil tillage (day 140) and 15 mm of precipitation; this indicates the influx of soil NO₃-N subsequent to soil disturbance. A drop in [NO₃-N] in the lower B_t after day 133 coincided with soil water depletion, and is attributed to rye root uptake of water and N as SWC was less than the



Figure 4.12 Seasonal trends in soil [NO3-N] observed by suction lysimeters and simulated by **CERES-Maize** for lysimeter CT 2, conventional tillage treatment with high initial residual NO₃-N. Simulated runs using time-to-ponding (TTP) and curve number (CN) methods of predicting infiltration, and RLD_{max} values of 5 or 2 cm cm⁻³.

drained upper limit (DUL). Data on soil [NO3-N] from suction lysimeters are not available after day 184 due to failure of soil water extraction.

Simulated soil [NO3-N] was lower than actual observations. The influx of soil NO3-N after day 142 was not reflected in simulated N transport processes. The TTP method of partitioning rainfall into infiltration resulted in higher soil N levels after day 190 relative to the CN This result is attributed to reduced infiltration method. and leaching for the TTP method as confirmed by lower SWC for TTP estimates of infiltration after day 180 (Figure 4.10B). Reducing RLDmax from 5.0 to 2.0 cm cm⁻³, slightly altered predictions of soil NO_3-N , due to effects on water and N extraction (Figure 4.12).

Seasonal trends in soil NO_3-N distributions reflected net effects of soil water transport, root uptake, and microbial transformations. Residual NO_3-N distributions in B_t horizons were moderate (CT 13) or very high (CT 2) for CT lysimeters but low (NT 6) to depleted (NT 9) for NT lysimeters, reflecting differences in solute retention induced by tillage effects. An increase in NO_3-N following tillage observed in CT 2 suggests solutes may be retained in regions of soil water that are resistant to leaching, unless disturbed by tillage. Simulation of seasonal trends in soil NO_3-N is sensitive to method of predicting infiltration, and slightly sensitive to RLD_{max} when soil water approached the lower limit of plant extractable SWC.

N Leaching Losses

Transport of NO3-N to the 3E\Bt horizon, observed in NT lysimeter, requires sufficient infiltration to displace solute bearing water held in upper horizons. The concentration of NO3-N in water drained below the root zone combines with drainage flux rate to determine nitrate leaching rates. Flux of water and N out the lysimeter are reported in this section, with consideration for soil and root effects on flux rates.

Lysimeter drainage occurred prior to day 150 and day 300 (Figure 4.13), corresponding to soil water depletion by root uptake and evaporation. Drainage flux from NT lysimeters exceeded that of the CT lysimeter, and persisted through the maize growing season. Reduced drainage under CT relative to NT is consistent with evidence of reduced infiltration under tillage and reduced soil water recharge (Figures 4.8 and 4.9).

Distributions of roots affect drainage by modifying the distribution of soil water extractions, and the magnitude of water extracted when soil supply limits canopy evaporation. Patterns of soil water extraction determine the distribution of soil water recharge that is required prior to drainage. Warner and Young (1991) demonstrated that root channels may provide preferential flow paths for applied water, due to stem flow and macropore flow along the root and soil interface.



Figure 4.13 Cumulative water and nitrate efflux 2.0 m below the soil surface observed or simulated by CERES-Maize for non-disturbed field lysimeters subjected to either notillage (A) cumulative drainage, **(B)** cumulative NO3-N leaching; or conventionnal tillage (C) cumulative drainage, (D) cumulative NO3-N leaching. Simulated runs using timeto-ponding number methods predicting and curve of infiltration, and RLD_{max} values of 5 or 2 cm cm⁻³.

The seasonal pattern of drainage prior to maize crop uptake of soil water is reflected in simulated drainage of both the CT and NT lysimeters (Figure 4.13). The simulation model indicates that drainage ceases during crop growth and underestimates drainage prior to crop water uptake. The model predicts soil drainage resumes at day 240 for both NT lysimeters, nearly two months prior to observed drainage for this treatment (Figure 4.13A). Reducing RLD_{max} from 5.0 to 2.0 cm cm-3 did not significantly modify drainage rates.

Seasonal patterns in NO₃-N leaching were nearly parallel with those observed in drainage flux, reflecting similar outflow concentrations among the lysimeters. This result illustrates the sensitivity of NO₃-N leaching predictions to errors in predicted soil water drainage. The relatively greater N leaching losses from NT 9 result from higher outflow concentrations, nearly twice that of the other lysimeters on day 122 (Figure 4.14). Inspection of cumulative leachate indicates a trend to decreasing leachate concentrations for NT lysimeters. This diminution of outflow concentration indicates the pulse of solute had already flowed through the soil prior to initial sampling on day 99, 1991 (Figure 4.13), assuming convective dispersion retarding solute flow (Jury et al., 1991). In contrast, outflow NO₃-N concentrations of CT lysimeters remained constant or increased slightly. This result confirms the "perched" profile distribution of soil N for CT2 (Figure 4.4B) indicating the pulse of solute had not leached prior to



Figure 4.14 Distribution of leacheate NO3-N concentrations with respect to cumulative outflow volume from non-disturbed field lysimeters subjected to either no-tillage (A) NT 6, (B) NT 9; or conventional tillage (C) CT 2, (D) CT 13.

initial sampling (day 99). The fluctuations in outflow concentrations, occurring when cumulative leachate was 75 mm, corresponds with low outflow rates during crop water uptake during the period from days 150 through 300 (Figure 4.13A and 4.13C). These fluctuations indicate vertical and/or horizontal mixing of solutes is greater at low efflux rates relative to high efflux rates.

The contrasting seasonal trend in NO_3-N concentration in drainage outflow for NT and CT lysimeters corroborate evidence of tillage-induced effects on solute retention. Cumulative precipitation (945 mm from day 213, 1990 through day 121, 1991) and irrigation (55 mm on days 322-325, 1990) following N application (day 212, 1990) was sufficient to exchange the entire pore volume of the soil profile. (Given profile-average saturated water content of 0.36, and profile depth of 2 m, total water filled pore volume of the soil profile is 720 mm.) Thus, NO3-N transport via leaching losses can account for the NO_3-N distributions observed under NT. However, retention of 49% to 61% of residual N in upper soil layers under CT (Figure 4.4) indicate solute transport characteristics of this Kalamazoo loam are modified by tillage.

Water draining from the lower boundary of each lysimeter was lower for CT than NT lysimeters; though drainage was substantially reduced during crop growth for all lysimeters (Figure 4.13A and C). Soil water recharge

and drainage throughout crop growth were higher for NT 6 than NT 9.

Nitrate leaching rates result from leacheate [NO3-N] and drainage flux from upper soil horizons. Reduced soil water recharge and increased NO3-N retention by A_{p} and B_{t} horizons for CT conform to trends in tillage effects on cumulative leacheate [NO3-N] (Figure 4.14). Leacheate [NO3-N] declined with cumulative water drainage for both NT lysimeters. This result indicates the peak pulse of solute passed through the 2.0 m profile prior to initial sampling on day 88, 1991. In contrast, leacheate [NO3-N] under CT 13 fluctuated about a nearly constant value of 100 mg L-1; and increased from around 75 mg L-1 to 150 mg L_{-1} for CT 2. These results suggest NO3-N transport under CT, with restricted infiltration, may be proportional to solute concentrations in upper soil layers, where NO₃-N may be retained, rather than moving as a uniform front through the soil matrix.

DISCUSSION

Retention of NO3-N in Bt horizons under CT but not NT is partially attributed to reduced infiltration and subsequent drainage. These tillage effects on the soil water budget are indicated by reduced soil water recharge (Figure 4.8A-D and Figure 4.9A and B) and cumulative drainage (Figure 4.13). Soil textural differences at horizon boundaries could affect solute retention. Nitrate

accumulations at the boundaries of the fine textured Bt horizon and coarse texture 3E/Bt horizon were detected among the lysimeters, though the quantities of NO3-N retained in lysimeters differ. Thus soil textural CT and NT discontinuities can account for NO3-N accumulations observed at horizon boundaries; but textural discontinuities are not sufficient to account for greater NO_3-N retention in B_+ horizons under CT relative to NT. Tillage modification of solute partitioning into micropore regions of soil water could interact with infiltration and horizon boundaries to account for the observed N retention.

Solute partitioning to a micropore region of soil water is represented in a dual region solute transport model (Jury et al., 1991,); which may help interpret differences in NO₃-N retention and transport associated with tillage treatments. When water is held in mobile (Θ_m) or immobile (Θ_{im}) regions, the convective dispersion equation (discussed in Chapter 1) can be expanded to partition solutes into mobile (N_m) and immobile (N_{im}) fractions:

$$\begin{array}{cccc} dN_{im} & dN_m & d^2N_m & dJ_wN_m \\ \Theta_{im} & ---- + \Theta_m & ---- = D_{-----} & ------ -r_s \\ dt & dt & dz^2 & dz \end{array}$$
 [4.15]

where D is mean effective hydrodynamic dispersion, z is soil depth and J_W is water flux. Solute exchange between mobile and immobile water regions is governed by concentration gradients and a transfer coefficient (α)

$$\frac{d\Theta_{im}N_{im}}{dt} = \alpha(N_m - N_{im}) \qquad [4.16]$$

Dual region solute transport theory suggests tillage effects on solute retention could occur especially when water infiltration and redistribution patterns are modified by tillage.

Conventional tillage increased the fraction of soil water held in macropores (effective pore diameters greater than 48 um) relative to no till at the same KBS field plots reported in this study (Reinert, 1990). Thus, more water may be partitioned into mobile regions for CT. If the solute transfer coefficient (α) of equation [4.16] also increases with tillage, solutes could diffuse more readily into immobile soil water under CT. Given sufficient diffusion time, a substantial fraction of solute could diffuse into water held in the immobile region, proportionate to the concentration gradient between the regions. Solutes would be leached from the immobile region during infiltration events, proportionate to concentration gradients $(N_m - N_{im})$ and the residence time of water held in the mobile region. Thus, a dual region solute transport model suggests tillage affects NO3-N retention by modifying the fraction of water held in mobile regions, and increasing the transfer coefficient for diffusion of solutes into water held in immobile regions.

Solute transport in leachate outflow was closely coupled with water flux in the mobile region. Thus, accuracy of solute transport predictions are sensitive to errors in predicted water flux. Factors regulating water flux in the soil matrix can shift relative to atmospheric boundary conditions and the state of soil water and corresponding transport characteristics. Accurate simulation of soil water flow, and associated solute transport, depends on specification of system state and correct boundary conditions, and the governing relationships. Errors in simulated system behaviour can result from failure to detect conditions when regulation of water flow shifts from boundary conditions to system processes.

Examples of shifting regulation of water flux can be found in both infiltration and evaporation at the soil surface. The time-to-ponding (TTP) method (Chou, 1990) of partitioning rain into runoff and infiltration components explicitly defines the rain or irrigation flux intensity (boundary condition) that exceeds the soil water transport capacity (system process). Regulation of infiltration shifts from boundary condition (surface flux) to soil system process (soil water transport capacity) when rain intensity exceeds the threshold value. Similarly, regulation of soil surface evaporation shifts from boundary condition (evaporative demand) to soil system process (soil water transport capacity) when a similar threshold condition is reached (Idso et al., 1974). The principle of regulatory

shifts from boundary conditions to system processes can be extended to water evaporation from a plant canopy by considering soil-root interactions as determinants of soil water transport capacity.

Unfortunately, atmospheric boundary conditions are quantified more readily than soil-plant interactions. Thus simulation error is likely to increase when regulation of water flux shifts from atmospheric boundary conditions to soil water transport processes. This shift tends to occur as rain intensity exceeds soil water transport capacity, and as evaporative demand exceeds soil water transport capacity. The remaining discussion is devoted to consequences of shifts in regulation of water flux, and simulation error.

Errors in simulated NO_3-N flux below the root zone are attributed to errors in simulated boundary conditions and soil-plant interactions. A principle error in boundary conditions for the soil water balance involves plant canopy development. Water stress effects on canopy development were not detected in simulated plant growth for CT lysimeters (Figure 4.6C); N stress effects on canopy development for NT lysimeters were overestimated (Figure 4.6A). These systematic biases altered simulated evaporative demand. Consequently, soil water depletion was overestimated for CT lysimeters and underestimated for NT lysimeters.

Underestimating the quantity of water required torecharge the soil profile resulted in errors in simulated drainage and NO_3 -N leaching. Soil water drainage and NO_3 -N

leaching was predicted to occur nearly 60 days prior to actual field observations for NT. This result occured because drainage with matric flow typically occurs only after soil water profile is recharged. CERES-Maize underestimated the quantity of water required to recharge the soil profile, thereby forcasting drainage and NO_3-N leaching prior to actual occurance.

In this study, soil system processes, rather than atmospheric boundary conditions, provided significant regulation of soil-plant interactions. Soil crusts, forming on the surface of CT lysimeters, restricted infiltration, thus reducing recharge of soil water available for transpiration, relative to NT lysimeters. Nitrogen supply for the NT lysimeters derived primarily fron net N mineralization from organic matter, since mineral N was largely depleted by the prior rye crop. Soil processes modified availability and distribution of water and N, thereby influencing growth and function of root and canopy elements.

Simulation of soil-plant interactions was improved when the shift in system regulation from boundary conditions to system processes was explicit. The time trend of SWC was more accurately depicted by the TTP method (defining threshold rain intensities that exceed soil water transport capacity) than by the CN method (assuming proportionate loss of rainfall to runoff). In the same way, simulated SWC was sensitive to the value assigned to maximum root length

density (RLD_{max}) only when simulated soil water depletion was restricted by soil water transport capacity. When SWC approached the lower limit of soil water supply, accuracy of simulated SWC was improved by reducing RLD_{max} from 5 to 2 cm cm⁻³, a value more consistent with field observations. We infer further gains in simulation accuracy may result when simulation structure correctly defines conditions when system regulation shifts from boundary conditions to system processes.

Previous chapters of this work demonstrate soil water depletion and crop development rates are modified by the non-uniform distribution of roots. Localized soil water depletion and corresponding root regulation of canopy shift regulation of water resistance can flux from conditions soil-plant interactions. atmospheric to Simulation of the soil water balance is expected to gain accuracy when effects of non-uniform distributions of water and roots, corresponding variations in soil-root hydraulic gradients, and subsequent root-shoot interactions are incorporated in simulation structures.

Soil-plant interactions can be predicted solely from environmental boundary conditions with some degree of accuracy when supply of growth factors (water and nutrients) is abundant. However, supply of growth factors are scarce for the large proportion of farmers with limited resources. Further, the dual objectives of optimizing productivity and nutrient retention implies 'just in time' supply of mobile

plant nutrients. Under conditions of scarcity, soil system processes, rather than environmental boundary conditions are likely to dominate regulation of soil-plant interactions.

Simplified analysis of root function, e.g. incorporating root distributions into "lumped" coefficients defining a time constant of soil water depletion, may be adequate for simulating the soil water balance under conditions of abundance. But sensitivity to heterogenous distributions of roots and soil water, and root effects on regulation of transpiration, assimilation and allocation processes may be required for simulation models that can guide water management practices under conditions of scarcity.

SUMMARY AND CONCLUSIONS

The architecture or geometric arrangement of root system elements is directly related to root function. The activity of meristematic tissue in root tips represents the fundamental element of root system development (Porter, Initiation and growth trajectories of root tips 1989). structure of root distributions, and the define the corresponding regions of rooted soil. Localized depletion of soil water can result in restricted root water uptake prior to root extension into wet soil. Maize canopy structure can thus be altered by transient water deficits during vegetative growth. The architecture of root systems can be understood as the dynamic modification of root tip growth modules in relation to soil structural features that interact with environmental factors to influence whole plant growth and development.

The cylindrical model of water and solute flux to root surfaces is the conceptual foundation of current research in root function. Analytic solutions to cylindrical flow are simplified by assumptions of uniform root distributions and constant soil-root hydraulic gradients. Non-uniform root distributions result from branching growth habits, root growth responses to heterogenous distributions of soil water and nutrients, and soil structural features. A horizontal

component to the root proliferation front was detected in intersections. with root exponential minirhizotron inter-root distances. Clustered distributions of root distributions at anthesis and grain fill growth stages were quantified by spatial correlation up to 0.45 m. Soil water depletion was restricted by the volume of rooted soil during mid-vegetative water deficits. Additional solutions to cylindrical flow models may gain accuracy be re-evaluating assumptions of xylem water potential and cylinder radius boundary conditions, taking into account the heterogenous distributions of roots and soil water.

A systematic bias was detected in a simplified solution to the cylindrical model of water flow to root surfaces. Predicted root water uptake, during extended drying cycles, increased with available water content at progressive soil depths. But observed soil water depletion rates decreased with soil depth prior to depletion of water in more shallow soil layers. Predictive error is attributed to the assumption of uniform soil-root hydraulic gradients, which neglects depth-dependent gradients in root xylem potential arising from frictional resistance in xylem vessels.

Integrating water uptake of single root segments to the scale of multiple root segments, or root networks requires theory beyond the cylindrical flow model. Analysis of root system behaviour can be improved by considering differential radial conductivity of suberized and non-suberized regions of roots (Russell, 1977), and by considering frictioninduced pressure drops in root xylem potential (Klepper et al., 1983). Effects of soil and root structural geometries on soil capacitance, e.g. the change in volumetric water content with respect to a pressure gradient, suggests a fresh approach to root-soil interactions.

Soil CO_2 profile distributions and vertical gradients in flux rates indicate soil plus root respiration violates the assumption of steady state. In situ sampling of CO_2 source strength requires a minimum sampling frequency of two samples per cycle of periodic fluctuation in CO2 source strength (Press et al., 1986, pp.386-7). Analysis of subsequent data requires a model that distinguishes transient changes in CO_2 partial pressures from CO_2 source/sink relations.

Retention of NO_3-N in B_t horizons of conventionally tilled, but not no-till soil is partially attributed to tillage effects on surface crusting and continuity of soil pores, resulting in differential infiltration rates and preferential flow paths. However, the time trend of solute concentrations in leachate indicate outflow concentrations may be proportionate to solutes stored in upper soil layers. A solute transport model distinguishing mobile and immobile regions of soil water is consistent with these observations, suggesting tillage can increase the rate of solute diffusion from water held in mobile and immobile soil regions.

Simulation of N leaching losses was sensitive to errors in soil water distribution, and corresponding drainage flux.

These errors can result when soil processes regulating infiltration and water redistribution, and soil-plant interactions regulating root water uptake are not correctly specified. Reducing simulated root length density from a maximum of 5.0 to 2.0 cm cm⁻³ did not alter simulation results, with the exception of root water uptake when soil water approached the lower limit of soil water supply. The time trend of simulated soil water recharge in the B_t horizon was more accurately portrayed by a time-to-ponding method of partitioning rain into runoff and infiltration components. This method explicitly specifies the conditions when regulation of infiltration rates shifts from boundary conditions (rain intensity) to system processes (soil water transport capacity).

Simulations of soil-plant interactions can guide water management practices for optimizing productivity and solute retention. A simplified approach to soil-plant interactions can be adequate to predict system behavior when supply of growth factors is abundant and boundary conditions regulate system processes. Analysis of complex soil-plant interactions may be required when supply of growth factors is limiting, for system behavior can be regulated by these interactions, as well as boundary conditions. Expanding our perspective on root function to consider effects on soil structure and transport processes, and on regulation of transpiration, assimilation and allocation of C can extend the validity of soil-plant management simulations.

CONCLUSIONS

1) The front of root initiation into soil volumes has horizontal as well as vertical components for row crops, with dimensions influenced by root lateral proliferation rates and growth trajectories of root tips.

2) Clustered, non-random root distributions are characterized by spatial correlation up to 0.45 m at anthesis, and by exponential distributions of inter-root distances that decline with root proliferation.

3) Restricted root proliferation can reduce soil water depletion prior to extensive growth into wet soil, thereby modifying transpiration, C assimilation, allocation, and canopy growth processes.

4) Vertical gradients in soil water depletion, not predicted by a simplified solution to a cylindrical model of root water uptake, are attributed to vertical gradients in root xylem potential.

5) Soil distributions of CO₂ correspond with greater root and soil organic matter accumulations, but violate steady state conditions, based on flux calculations.

6) Greater retention of NO_3-N in fine-textured B_t horizons of a layered soil for conventional till, but not no-till treatments suggests tillage reduced barriers to solute diffusion between mobile and immobile regions of soil water.

7) Deviations in NO₃-N concentrations of leachate from seasonal trends coincide with extreme high or low drainage flux conditions, indicating assumptions of homogeneous pore velocities and concentrations are invalid.

8) Simulated NO_3 -N leaching losses were sensitive to errors in predicted soil water associated with infiltration, canopy dimensions, and subsequent drainage below the root zone; but not to reductions in maximal root length density from 5 to 2 cm cm⁻³, a value more consistent with field observations.

9) The time trend of soil water content in the B_t horizon was more accurately portrayed by a time to ponding method of partitioning rain into runoff and infiltration, explicitly defining the shift in system regulation from atmospheric boundary conditions to soil system processes.

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APPENDIX

Initial and boundary conditions for CERES-Maize v2.1 simulation of soil-plant interactions (IBSNAT, 1985).

Weather Input File "MSKB9101.MZ1

LOC	YR	DAY	Rq	Tmax	Tmin	Ppt	TTP
MSKB	91	121	12.5	13.0	7.7	0.0	0.0
MSKB	91	122	24.7	13.6	4.1	0.0	0.0
MSKB	91	123	25.6	16.7	1.0	0.0	0.0
MSKB	91	124	20.0	18.7	6.6	0.0	0.0
MSKB	91	125	4.1	14.9	6.8	6.0	6.0
MSKB	91	126	4.3	14.6	5.7	0.7	0.7
MSKB	91	127	21.8	13.9	3.3	0.0	0.0
MSKB	91	128	12.4	16.4	3.1	0.0	0.0
MSKB	91	129	25.0	26.4	7.7	0.0	0.0
MSKB	91	130	24.9	26.5	9.8	0.0	0.0
MSKB	91	131	21.8	28.9	12.0	0.0	0.0
MSKB	91	132	24.3	31.0	15.4	0.0	0.0
MSKB	91	133	20.9	30.9	14.9	0.0	0.0
MSKB	91	134	25.4	29.7	14.0	0.0	0.0
MSKB	91	135	27.8	32.7	10.5	0.0	0.0
MSKB	91	136	20.8	31.7	15.4	0.0	0.0
MSKB	91	137	14.2	24.5	6.7	0.7	0.7
MSKB	91	138	18.5	16.0	6.2	0.0	0.0
MSKB	91	139	27.5	22.2	7.2	16.5	6.5
MSKB	91	140	26.4	27.3	7.9	0.0	0.0
MSKB	91	141	24.5	29.6	10.4	0.0	0.0
MSKB	91	142	19.0	30.3	15.4	0.0	0.0
MSKB	91	143	11.3	27.2	19.2	9.6	9.6
MSKB	91	144	16.9	28.4	19.7	0.5	0.5
MSKB	91	145	9.2	27.1	19.7	2.5	2.5
MSKB	91	146	15.3	26.6	21.1	1.3	1.3
MSKB	91	147	23.8	29.9	20.3	1.0	1.0
MSKB	91	148	24.7	32.3	19.5	0.0	0.0
MSKB	91	149	21.3	33.5	21.8	0.0	0.0
MSKB	91	150	23.5	31.1	19.5	0.0	0.0
MSKB	91	151	24.1	31.6	19.5	18.0	18.0
MSKB	91	152	17.6	31.2	17.4	1.7	1.7
MSKB	91	153	19.0	27.8	17.7	11.4	11.0
MSKB	91	154	24.7	29.0	13.8	0.0	0.0
MSKB	91	155	29.75	28.3	16.1	0.0	0.0
MSKB	91	156	23.97	28.3	9.4	0.0	0.0
MSKB	91	157	27.37	23.8	8.3	0.0	0.0
MSKB	91	158	20.59	26.1	8.8	0.0	0.0
MSKB	91	159	28.63	26.6	13.3	0.0	0.0
MSKB	91	160	23.97	27.2	12.7	0.0	0.0
MSKB	91	161	18.23	28.8	12.7	0.0	0.0
MSKB	91	162	13.26	28.8	15.5	0.0	0.0
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MSKB	91	163	28.19	26.1	18.3	0.0	0.0
MSKB	91	164	29.03	28.3	14.9	0.0	0.0
MSKB	91	165	25.70	28.3	11.6	0.0	0.0
MSKB	91	166	18.72	31.6	15.5	9.0	9.0
MCKB	01	167	17.34	31.1	18.8	0.0	0.0
MCVD	01	169	21 11	29 A	18.8	0.0	0.0
MOVD	91	160	32.17	22.3	12 2	0.0	0.0
MOND	91 91	107	20.22	20.J	15.5	0.0	0.0
MOND	91	170	29.13	30.5 20 E	16 6	0.0	0.0
MSKB	91	1/1	29.05	30.5	17.0	0.0	0.0
MSKB	91	1/2	27.04	31.0	17.2	12 0	12 0
MSKB	91	173	4.20	32.2	1/.2	13.0	13.0
MSKB	91	174	30.57	32.2	13.8	0.0	0.0
MSKB	91	175	25.78	24.4	10.5	6.0	6.0
MSKB	91	176	26.97	27.2	11.6	0.0	0.0
MSKB	91	177	27.70	30.5	16.1	0.0	0.0
MSKB	91	178	25.54	31.1	16.1	3.0	3.0
MSKB	91	179	23.85	31.6	20.5	0.0	0.0
MSKB	91	180	25.35	31.1	20.5	0.0	0.0
MSKB	91	181	24.39	32.2	22.2	0.0	0.0
MSKB	91	182	18.98	32.7	23.3	51.0	20.0
MSKB	91	183	24.98	30.5	17.7	1.0	1.0
MSKB	91	184	26.80	30.5	19.4	15.0	9.5
MSKB	91	185	23.30	29.9	19.4	4.0	4.0
MSKB	91	186	27.10	29.4	18.3	0.0	0.0
MSKB	91	187	23.94	34.9	18.8	0.0	0.0
MSKB	91	188	17.72	31.1	17.2	16.0	16.0
MSKR	91	189	29.21	29.4	22.2	0.0	0.0
MSKB	91	190	26.59	30.5	19.9	0.0	0.0
MSKB	91	191	23.69	26.6	11.6	0.0	0.0
MCKB	91	192	28.49	27.2	14.9	0.0	0.0
MCKB	<u>01</u>	103	10 45	29 A	16.1	16.0	11.0
MCKD	01	101	0 54	22.4	16 1	3 0	3.0
MOND	7	105	2.54	20.0	16 1	1.0	1 0
MOND	21	106	21.37	21.1	15 5	1.0	1.0
MCKD	91	107	27.00	20.0	12.5	0.0	0.0
MOND	91	197	23.20	2/./	13.3	0.0	0.0
MSKB	91	198	21.05	29.4	14.4	0.0	0.0
MSKB	91	199	23.29	29.4	10.1	0.0	0.0
MSKB	91	200	26.01	31.0	19.4	0.0	0.0
MSKB	91	201	22.87	32.2	21.1	0.0	0.0
MSKB	91	202	15.61	32.2	23.3	13.0	13.0
MSKB	91	203	16.97	32.2	21.6	77.0	29.0
MSKB	91	204	28.27	31.6	21.1	0.0	0.0
MSKB	91	205	26.33	32.2	21.6	0.0	0.0
MSKB	91	206	26.40	26.1	15.5	0.0	0.0
MSKB	91	207	24.20	24.9	14.9	0.0	0.0
MSKB	91	208	24.99	24.4	11.1	0.0	0.0
MSKB	91	209	20.17	26.6	10.5	0.0	0.0
MSKB	91	210	3.94	26.6	14.9	8.0	8.0
MSKB	91	211	21.92	25.5	14.9	0.0	0.0
MSKB	91	212	25.87	23.8	14.4	0.0	0.0
MSKB	91	213	26.85	28.3	12.7	0.0	0.0
MSKB	91	214	20.00	29.4	18.8	9.0	9.0
MSKB	91	215	8.81	31.6	16.1	12.0	6.5

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MSKB	91	216	21.43	31.6	18.3	18.2	18.2
MSKB	91	217	23.30	24.4	13.8	0.0	0.0
MSKB	91	218	25.32	23.8	10.5	0.0	0.0
MSKB	91	219	21.17	26.1	11.6	0.0	0.0
MSKB	91	220	1.84	27.2	13.8	31.0	31.0
MSKB	91	221	22.85	26.6	13.8	0.0	0.0
MSKB	91	222	24.38	26.1	13.3	0.0	0.0
MSKB	91	223	25.82	26.6	12.7	0.0	0.0
MSKB	91	224	23.16	27.7	12.7	0.0	0.0
MSKB	91	225	22.42	27.7	13.3	0.0	0.0
MSKB	91	226	21.59	28.3	13.3	0.0	0.0
MSKB	91	227	20.35	28.3	14.9	0.0	0.0
MSKB	91	228	20.61	28.3	14.9	0.0	0.0
MSKB	91	229	11.90	28.8	18.3	3.0	3.0
MSKB	91	230	16.84	28.8	19.9	33.0	15.5
MSKB	91	231	2.71	26.6	14.9	41.0	41.0
MSKB	91	232	21.28	21.6	15.5	0.0	0.0
MSKB	91	233	21.28	24.9	14.4	0.0	0.0
MSKB	91	234	22.09	26.1	11.6	0.0	0.0
MSKB	91	235	23.66	29.4	19.9	0.0	0.0
MSKB	91	236	23.19	28.3	13.3	0.0	0.0
MSKB	91	237	22.19	28.8	14.9	0.0	0.0
MSKB	91	238	21.51	31.6	14.9	0.0	0.0
MSKB	91	239	21.46	31.1	18.3	0.0	0.0
MSKB	91	240	21.40	30.5	18.8	0.0	0.0
MSKB	91	241	15.02	32.2	19.4	0.0	0.0
MSKB	91	241	15.34	32.2	19.4	0.0	0.0
MSKB	91	242	20.42	31.1	20.5	0.0	0.0
MCKB	01	243	20.42	20 A	16 6	0.0	0.0
MCVD	91 01	244	11 23	25.5	10.0 A	0.0	0.0
MOKD	91	245	11.03	23.3	9.4 Q A	7 0	7.0
MCKB	01	240	18 69	27 7	16.6	0.0	0.0
MCVD	91 01	247	17 05	26 6	12 2	0.0	0.0
MOND	91 01	240	17 01	20.0	0 0	0.0	0.0
MOND	91 01	247	10 22	25.5	11 6	0.0	0.0
MOND	91 01	250	10.23	27.7	14 4	0.0	0.0
MOVD	91 01	251	17 /3	29.9	15 5	5.0	5.0
MCVD	91 01	252	12 04	21 6	10 2	2.0	2.0
MOND	91	255	10 20	20 0	10.3	0.0	0.0
MOVD	91 01	204	10.30	23.3	TO . 2	0.0	0.0
MOND	91 01	200	0.00	20.0	7.4 10 7	12 0	12 0
MOVD	91 01	250	6.39	22.2	16 6	2.0	2.0
MOND	91	20/	0.14 15 02	22.1	15.5	2.0	2.0
MOND	91	200	12.03	23.0	12.2	3.0	3.0
MOND	91	209	17 70	29.9	20.5	0.0	0.0
MOND	91	200	11 25	29.4	21.1	0.0	0.0
MOKD	91	201	11.25	24.4	14.9	3.0	3.0
MOND	91 AT	202	10.40	46.6	16.6	0.0	0.0
MOVE	01 AT	205	10 50	12.7	1.2	0.0	0.0
MOND	21	204	TA.02	17 2	4.9	0.0	0.0
MOKE	AT AT	200	0.09	17.2		4.0	4.0
MSKB	AT N	200	12.32	1/./	T.0	4.0	4.0
MSKB	91	207	0.89	10.0	8.8	0.0	0.0
MSKB	91	268.	3.95	14.9	4.9	3.0	3.0
MSKB	91	269	13.47	13.3	2.7	4.0	4.0

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MSKB	91	270	15.34	12.7	6.6	0.0	0.0
MSKB	91	271	18.33	13.3	1.1	0.0	0.0
MSKB	91	272	16.34	17.2	-1.1	0.0	0.0
MSKB	91	273	15.33	19.9	-1.6	0.0	0.0
MSKB	91	274	11.75	25.5	7.7	0.0	0.0

Rg is global radiation (Mg m⁻²) Tmax is maximum daily temperature (°C) Tmin is minimum daily temperature (°C) Ppt is daily precipitation (mm) TTP is time-to-ponding estimate of infiltration for crusted soil, conventional tillage. This method assumes soil intake of the initial 2 mm of precipitation but runoff for rainfall exceeding 3 mm h⁻¹ (Aiken, 1992, pp 105-106)

98 CT Lys #2 Kalamazoo loam, mixed, mesic Udic Haplustoll 0.13 7. 0.4 84.0 8.5 13.5 1. 2.67E-3 58.0 6.68 0.03 1.0 5.0 5. 0.13 0.33 0.41 0.31 1.00 1.5 2.8 3.0 41.9 6.5 5. 0.13 0.33 0.41 0.31 1.00 1.5 2.8 3.0 41.9 6.5 11. 0.13 0.31 0.33 0.41 0.81 1.5 1.7 3.0 41.9 6.5 0.42 0.27 0.64 1.47 0.9 8.4 84.9 6.5 11. 0.13 0.27 0.27 1.47 0.9 11. 0.13 0.26 0.42 0.49 5.0 116. 6.5 0.36 1.47 0.9 3.8 153. 11. 0.10 0.24 0.42 0.28 6.5 12. 0.05 0.18 0.37 0.22 0.25 1.61 0.7 2.9 94.9 6.5 2.1 12. 0.05 0.14 0.37 0.15 0.14 1.61 0.5 57.1 6.5 20. 0.05 0.14 0.34 0.14 0.05 1.7 0.2 2.0 43.6 6.5 0.1 21. 0.05 0.14 0.34 0.14 0.01 1.7 1.8 37.4 6.5 21. 0.05 0.14 0.34 0.14 0.0 1.7 0.05 1.5 31.0 6.5 0.01 1.4 21. 0.05 0.14 0.34 0.14 0.0 1.7 24.8 6.5 1.7 21. 0.05 0.14 0.34 0.14 0.0 0.01 1.3 18.4 6.5 0.14 1.7 0.01 1.2 21. 0.05 0.34 0.14 0.0 12.1 6.5 -1. 97 CT Lys #13 Kalamazoo loam, mixed, mesic Udic Haplustoll 0.13 7. 0.4 84. 8.5 13.5 1. 2.67E-3 58. 6.68 0.03 1.0 5.0 5. 0.13 0.33 0.43 0.31 1.00 1.46 2.8 0.01 .01 6.5 6. 0.13 0.33 0.43 0.31 1.00 1.46 2.8 0.01 .01 6.5 11. 0.13 0.33 0.43 0.31 0.81 1.46 1.7 0.01 .01 6.5 0.40 10. 0.22 0.31 0.32 0.64 1.55 0.9 0.01 .01 6.5 10. 0.19 0.31 0.40 0.31 0.49 1.52 0.9 0.01 4.9 6.5 10. 0.15 0.31 0.36 1.52 0.9 0.40 0.31 0.5 12.0 6.5 10. 0.11 0.27 0.40 0.30 0.25 1.52 0.7 0.5 18.6 6.5 11. 0.09 0.27 0.38 0.26 0.14 1.59 0.5 0.5 21.6 6.5 11. 0.05 0.22 0.38 0.20 0.05 1.59 0.2 0.4 17.1 6.5 20. 0.05 0.11 0.34 0.11 0.01 1.72 0.1 0.1 2.6 6.5 20. 0.05 0.11 0.34 0.0 0.11 1.7 0.05 1.1 6.7 6.5 20. 0.05 0.11 0.34 0.11 0.0 1.7 0.01 1.1 6.7 6.5 20. 0.05 0.11 6.7 6.5 0.34 0.11 0.0 1.7 0.01 1.1 20. 0.05 0.11 0.34 1.7 0.11 0.0 0.01 1.1 6.7 6.5 19. 0.05 0.11 0.34 0.01 1.1 6.6 6.5

Soil Input File "MSKB9101.MZ2

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0.11 0.0 1.7

96	NT	Lys	# 6	Kala	amazoo) loam,	mixed	l, mes	sic Ud	lic Ha	aplust	toll
0.13	9	. 0.6	78.	8.5	5 13.5	1. 2.	67E-3	58. 6	5.68 (0.03	1.0	5.0
5	. (0.14	0.3	31 (0.42	0.31	1.00	1.49	2.8	0.01	0.04	6.5
5	. (0.14	0.3	31 (0.42	0.31	1.00	1.49	2.8	0.01	0.04	6.5
10	. (0.14	0.3	31 (0.42	0.31	0.92	1.49	1.7	0.01	0.04	6.5
9	. (0.18	0.3	35 (0.40	0.32	0.82	1.54	0.9	0.1	0.04	6.5
10	. (0.20	0.3	35 (0.38	0.33	0.73	1.58	0.9	0.01	0.01	6.5
10	. (0.20	0.3	34 (0.38	0.31	0.63	1.58	0.9	0.01	0.02	6.5
10	. (0.20	0.3	34 (0.38	0.31	0.52	1.58	0.7	0.4	0.03	6.5
10	. (0.09	0.2	22 ().34	0.25	0.41	1.69	0.5	0.3		
10	. (0.08	0.1	L9 ().34	0.16	0.29	1.69	0.4	0.01	3.7	6.5
11.	. (0.05	0.1	L 4 ().34	0.14	0.16	1.7	0.2	0.01	0.5	6.5
11.	. (0.05	0.1	L 4 (0.34	0.14	0.02	1.7	0.1	0.01	0.7	6.5
25	. (0.05	0.1	L 4 ().34	0.14	0.01	1.7	0.01	0.2	1.7	6.5
25	. (0.05	0.1	L 4 ().34	0.14	0.0	1.7	0.01	0.7	3.5	6.5
25	. (0.05	0.1	.4 ().34	0.14	0.0	1.7	0.01	0.9	5.3	6.5
27	. (0.05	0.1	4 0).34	0.14	0.0	1.7	0.01	1.1	7.1	6.5
-1	•											
95 1	TN	Lys ;	# 9	Kala	mazoo	loam,	mixed	l, mes	ic Ud	lic Ha	plust	:011
95 1 0.13	NТ 9.	Lys ; 0.6	# 9 78.	Kala 8.5	amazoo 5 13.5	loam, 1. 2.	mixed 67E-3	l, mes 58.6	ic Ud .68 0	lic Ha .03	aplust 1.0	:011 5.0
95 1 0.13 5.	УТ 9. . С	Lys ; 0.6).14	#9 78. 0.3	Kala 8.5	amazoo 5 13.5).41	loam, 1. 2. 0.31	mixed 67E-3 1.00	l, mes 58.6 1.50	ic Ud .68 0 2.8	lic Ha .03 0.1	plust 1.0 0.06	:011 5.0 6.5
95 1 0.13 5. 5.	TN 9. . (Lys; 0.6).14).14	#9 78. 0.3 0.3	Kala 8.5 1 (amazoo 5 13.5).41).41	loam, 1. 2. 0.31 0.31	mixed 67E-3 1.00 1.00	l, mes 58.6 1.50 1.50	ic Ud .68 0 2.8 2.8	lic Ha 0.03 0.1 0.1	aplust 1.0 0.06 0.06	011 5.0 6.5 6.5
95 1 0.13 5. 5. 10.	TN 9. . C . C	Lys; 0.6).14).14).14	# 9 78. 0.3 0.3 0.3	Kala 8.5 1 0 1 0	amazoo 5 13.5).41).41).41	loam, 1. 2. 0.31 0.31 0.31	mixed 67E-3 1.00 1.00 0.92	l, mes 58.6 1.50 1.50 1.50	ic Ud .68 0 2.8 2.8 1.7	lic Ha 0.03 0.1 0.1 0.01	plust 1.0 0.06 0.06 0.06	011 5.0 6.5 6.5 6.5
95 1 0.13 5. 10. 10.	9 . 9 . . 0 . 0 . 0	Lys; 0.6).14).14).14).14	#9 78. 0.3 0.3 0.3	Kala 8.5 1 (1 (1 (5 (amazoo 5 13.5).41).41).41).41	loam, 1. 2. 0.31 0.31 0.31 0.32	mixed 67E-3 1.00 1.00 0.92 0.82	l, mes 58.6 1.50 1.50 1.50 1.54	ic Ud .68 0 2.8 2.8 1.7 0.9	lic Ha 0.03 0.1 0.1 0.01 0.01	plust 1.0 0.06 0.06 0.06 0.06	coll 5.0 6.5 6.5 6.5 6.5
95 1 0.13 5. 10. 10. 8.	YT 9. 0. 0. 0. 0.	Lys; 0.6).14).14).14).14).20).20	#9 78. 0.3 0.3 0.3 0.3	Kala 8.5 1 0 1 0 1 0 5 0 6 0	amazoo 5 13.5).41).41).41).40).37	loam, 1. 2. 0.31 0.31 0.31 0.32 0.35	mixed 67E-3 1.00 1.00 0.92 0.82 0.73	l, mes 58.6 1.50 1.50 1.50 1.54 1.61	sic Ud 5.68 0 2.8 2.8 1.7 0.9 0.9	lic Ha 0.03 0.1 0.1 0.01 0.1 0.01	plust 1.0 0.06 0.06 0.06 0.06 0.01	<pre>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>></pre>
95 1 0.13 5. 10. 10. 8. 8.	TN 9. 0. 0. 0. 0. 0.	Lys; 0.6).14).14).14).20).20).20	<pre>#9 78. 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.</pre>	Kala 8.5 1 0 1 0 1 0 5 0 6 0 3 0	amazoo 5 13.5).41).41).41).40).37).37	loam, 1. 2. 0.31 0.31 0.32 0.35 0.33	mixed 67E-3 1.00 1.00 0.92 0.82 0.73 0.63	l, mes 58.6 1.50 1.50 1.50 1.54 1.61 1.61	ic Ud .68 0 2.8 2.8 1.7 0.9 0.9 0.9	lic Ha 0.03 0.1 0.1 0.01 0.1 0.01 0.1	plust 1.0 0.06 0.06 0.06 0.06 0.01 0.01	011 5.0 6.5 6.5 6.5 6.5 6.5 6.5
95 1 0.13 5 10 10 8 8 11	NT 9. 0. 0. 0. 0. 0. 0. 0.	Lys; 0.6).14).14).14).20).20).20).20	<pre>#9 78. 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.</pre>	Kala 8.5 1 0 1 0 5 0 6 0 3 0 2 0	amazoo 5 13.5).41).41).41).40).37).37).36	loam, 1. 2. 0.31 0.31 0.32 0.35 0.33 0.22	mixed 67E-3 1.00 1.00 0.92 0.82 0.73 0.63 0.52	l, mes 58.6 1.50 1.50 1.50 1.54 1.61 1.61	ic Ud .68 0 2.8 2.8 1.7 0.9 0.9 0.9 0.7	lic Ha 0.03 0.1 0.01 0.01 0.01 0.1 0.1 0.01	plust 1.0 0.06 0.06 0.06 0.06 0.01 0.01 0.01	oll 5.0 6.5 6.5 6.5 6.5 6.5 6.5 6.5
95 1 0.13 5 10 10 8 8 11 14	TR 9. 0. 0. 0. 0. 0. 0. 0.	Lys; 0.6).14).14).14).20).20).20).09).05	<pre>#9 78. 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.1 </pre>	Kala 8.5 1 0 1 0 5 0 6 0 3 0 2 0 .9 0	amazoo 5 13.5).41).41).41).40).37).37).36).36	loam, 1. 2. 0.31 0.31 0.32 0.35 0.33 0.22 0.18	mixed 67E-3 1.00 1.00 0.92 0.82 0.73 0.63 0.52 0.35	l, mes 58.6 1.50 1.50 1.54 1.61 1.61 1.65 1.65	ic Ud .68 0 2.8 2.8 1.7 0.9 0.9 0.9 0.7 0.5	lic Ha 0.03 0.1 0.01 0.01 0.01 0.1 0.01 0.01	plust 1.0 0.06 0.06 0.06 0.01 0.01 0.01 0.01	011 5.0 6.5 6.5 6.5 6.5 6.5 6.5 6.5 6.5
95 1 0.13 5 10 10 8 8 11 14 14		Lys; 0.6).14).14).20).20).20).20).09).05).05	<pre>#9 78. 0.3 0.3 0.3 0.3 0.3 0.3 0.3 0.1 0.1</pre>	Kala 8.5 1 0 1 0 5 0 6 0 3 0 2 0 .9 0	amazoo 5 13.5).41).41).41).40).37).37).36).36).36	loam, 1. 2. 0.31 0.31 0.32 0.35 0.33 0.22 0.18 0.16	mixed 67E-3 1.00 1.00 0.92 0.82 0.73 0.63 0.52 0.35 0.20	l, mes 58. 6 1.50 1.50 1.54 1.61 1.65 1.65 1.65	ic Ud .68 0 2.8 2.8 1.7 0.9 0.9 0.9 0.7 0.5 0.4	lic Ha 0.03 0.1 0.01 0.01 0.01 0.01 0.01 0.01	aplust 1.0 0.06 0.06 0.06 0.01 0.01 0.01 0.01	011 5.0 6.5 6.5 6.5 6.5 6.5 6.5 6.5 6.5 6.5
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