Modeling Nitrate Movement in Sugarbeet Soils under Flood and Drip Irrigation

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Abstract

Nitrate (NO₃) contamination is a continued global concern in many sugarbeet growing areas under flood irrigation. Use of drip irrigation can offer an alternative pollution control technology. With the objectives of comparing the effects of drip and flood irrigation on NO₃ movement in sugarbeet soils, a computer simulation study was conducted using a transport and irrigation model and the simulation results were compared with field data. Four irrigation treatments, including 20% (Drip 1), 35% (Drip 2), 50% (Drip 3), and 65% (Flood) water depletion of field capacity, were tested. At any given time, soil NO₃ concentrations followed the order of Drip 1 > Drip 2 > Drip 3 >> Flood. The higher irrigation frequency with minimal quantity of water corresponding to the least depletion percentage was found to be the best scheduling scheme for retaining NO₃ in soils. Throughout the irrigation period, greater (an average of 5 times) concentration-depth gradients for all three drip regimes, as compared to flood, were predicted by the simulations, indicating lower NO₃ loss with drip at any profile-depth. Kinetic analysis indicated that the rate of NO₃ movement under flood irrigation was 2 to 3.5 times faster than with the three drip regimes. The slowest leaching rate for Drip 1 was an indication of longer residence phase of NO₃ in soils during the growing season. As compared to flood, the half-life of NO₃ was nearly 3.5, 2.5, and 2.0 times greater under Drip 1, Drip 2, and Drip 3, respectively. Simulations predicted the residual soil NO₃ (RSN) followed the order of Drip 1 > Drip 2 > Drip 3 > Flood. Higher RSN values for the drip regimes suggested less NO₃ depletion and greater NO₃ availability as basal dose for the following crop. Simulation results were not significantly different from the actual data on soil NO₃ content and yield ratios obtained with field experiments (P < 0.05). This indicated that the simulation results could be utilized to understand in situ behavior of NO₃, which would be otherwise difficult or expensive to determine directly by field sampling and characterization.

Résumé

La contamination par les nitrates (NO₃) est une préoccupation continuelle dans de nombreuses régions sous cultures de betteraves irriguées par submersion. L’irrigation par goutte-à-goutte peut être une technologie alternative pour contrôler la pollution. L’étude présentée a pour objectifs de comparer les effets de l’irrigation goutte-à-goutte et par submersion sur le mouvement de NO₃ dans des sols sous culture de betteraves. Une simulation informatique a été menée en utilisant un modèle de transport et d’irrigation, et les résultats des simulations ont été comparés à des données recueillies au cours d’expérimentations. Quatre niveaux d’irrigation comprenant 20% (goutte-à-goutte 1), 35% (goutte-à-goutte 2), 50% (goutte-à-goutte 3), et 65% (submersion) de déficit hydrique par rapport à la capacité au champ, ont été testés. A chaque instant, les concentrations de NO₃ dans le sol suivent l’ordre Goutte-à-goutte 1 > Goutte-à-goutte 2 > Goutte-à-goutte 3 >> Submersion. La meilleure méthode pour conserver NO₃ dans les sols était d’irriguer le plus...
fréquemment avec une quantité minimale d'eau, ce qui correspondait au plus faible pourcentage de déficit hydrique. Durant la période d'irrigation, des gradients plus élevés de concentration avec la profondeur (5 fois en moyenne) ont été simulés pour les trois traitements goutte-à-goutte, par rapport à l'irrigation par submersion, ce qui indique une moindre perte de NO₃ dans l'irrigation goutte-à-goutte. L'analyse a indiqué que la vitesse du mouvement de NO₃ sous irrigation par submersion était 2 à 3,5 fois plus rapide que pour les trois traitements goutte-à-goutte. Le plus faible taux de lessivage pour le goutte-à-goutte 1 implique une plus longue période de résidence du NO₃ dans le sol pendant la saison de culture. Par rapport à l'irrigation par submersion, la demi-vie de NO₃ était 3,5, 2,5, et 2,0 fois plus longue avec les traitements Goutte-à-goutte 1, Goutte-à-goutte 2, Goutte-à-goutte 3, respectivement. Les simulations ont prédit que le NO₃ résiduel dans le sol (RSN) suivait l'ordre de Goutte-à-goutte 1 > Goutte-à-goutte 2 > Goutte-à-goutte 3 > Submersion. Des valeurs plus élevées de RSN pour les traitements goutte-à-goutte ont suggéré une moindre perte de NO₃ et un plus grand relai de NO₃ disponible comme pour la culture suivante. Les résultats des simulations ne sont pas très différents de ceux obtenus par expérimentation sur le taux de NO₃ dans le sol et les rendements ($P < 0.05$). Ceci indique que les résultats des simulations peuvent être utilisés pour comprendre le comportement de NO₃, qui autrement serait difficile ou coûteux à déterminer directement par échantillonnage et caractérisation au champ.

**Introduction**

With the growing concern about agricultural pollution due to fertilizer use, movement of contaminant solutes in soils, such as nitrate (NO₃⁻), needs to be understood under low-volume irrigation practices that can be utilized for management purposes. In many flood irrigated sugarbeet growing areas of Wyoming, NO₃ has been detected in groundwaters at levels exceeding the 10 mg L⁻¹ NO₃-N critical EPA limit (Baker and Associates Consulting Engineers, 1989; Wyoming Hydrogram, 1995). Because of high cash value of sugarbeet crops and concurrent contamination problems associated with NO₃, it is necessary to adopt new agricultural approaches that can lead to best management practices for sugarbeet production and contamination control. Use of drip irrigation, a novel approach for sugarbeet production in Wyoming, can offer such an alternative technology (Gregory, 1990; Caswell, 1991; Bucks, 1995). In a study comparing NO₃ transport to groundwater under drip and flood irrigation, Geleta et al. (1994) concluded that drip practice resulted in lower NO₃–N loss. The agronomic study of Roth et al. (1995) on oranges revealed that the reduced water use with drip irrigation did not affect fruit yield and quality.

Computer modeling can be useful for simulating NO₃ distribution under drip and flood irrigation practices. The numerical models, proposed by Molina et al. (1984), Hutson and Wagenet (1992), and RZWQM team (1995), have been extensively used in the literature to simulate water flow, nitrate transport, and plant uptake in irrigated and N fertilized soils. Ma et al. (1998) used RZWQM (Root Zone Water Quality Model) to predict water and soil NO₃ distribution in an irrigated corn field and obtained good agreement between measured and simulated values. Jabro et al. (1993) evaluated NO₃ leaching in a corn field with LEACHM (Leaching Estimation And Chemical Model) and NCSWAP (Nitrogen, Carbon, Soil, Water And Plant) and observed poor predictions below the 1.2-m soil depth. Numerous other models have been developed to simulate water and solute transport with drip irrigation. Sen et al. (1992) and Pal et al. (1992) proposed a simplified two-dimensional numerical model to predict water transport under drip irrigation in different textured soils. In a study on two-dimensional water distribution modeling under drip practice, Coelho and Or (1996) proposed the use of parametric models of water uptake with Bivariate Gaussian distribution density functions. Velledis
and Smajstrla (1992) developed a two-dimensional mathematical model to simulate soil water redistribution under drip irrigation using an implicit finite difference scheme and obtained good correlation results with experimental data on tomatoes. Cardon and Letey (1992) developed a modified van Genuchten-Hanks model to simulate water flow and solute movement under various irrigation regimes in the vertical direction using the Richards’ equation. However, all these studies are limited to 1- and 2- dimensional physical problems with simplified assumptions that do not accurately represent the more complex 3-dimensional system observed under drip irrigation. Numerical solutions have also been developed to solve the 3-dimensional flow equation for drip irrigation (Omary and Ligon, 1992; Clausnitzer and Hopmans, 1994; Nakayama and Bucks, 1986). Lafolie et al. (1989) modified a numerical model for simulating drip irrigation that improved water content predictions in stratified and anisotropic soils. These models however did not consider irrigation scheduling as a possible variable in a 3-dimensional soil system. Based on a water flow and solute transport model CHAIN_2D (Simunek and van Genuchten, 1994), and incorporating irrigation scheduling parameters, Zhang (1997) developed a model, CHAIN_IR, to simulate water flow and solute transport under flood and drip irrigation conditions.

Prior to large-scale implementation of low-volume irrigation practices, it is necessary to assess the comparative effects of drip and conventional flood irrigation on NO$_3$ movement and crop yield indices. Therefore, the objectives of this study were to determine the influence of drip and flood irrigation on NO$_3$ movement using computer simulations and to compare the simulation results with field-experimental data.

Materials and Methods

The computer simulations were carried out, using an irrigation and transport model CHAIN_IR (Zhang, 1997), in conjunction with a field study on sugar beet production under drip and flood irrigation. Field work was conducted at the Torrington Research and Extension Center, TREC, (elevation > 1200 m), in southeastern Wyoming, where NO$_3$ contamination is a continued concern and sugar beet is a major source of revenues (Wyoming Agricultural Statistics Service, 1998). Cassel Sharmasarkar (1998) described details of the field experiments elsewhere. The soils at TREC were classified as Daily sandy loams (sandy, mixed, mesic, Torriorthentic Haplustoll). Sand content percentages in the 0-45 cm, 45-90 cm, 90-135 cm, and 135-150 cm soil layers were 77%, 85%, 89%, and 90%, respectively; bulk densities for the same depths reached 1.69, 1.70, 1.84, and 1.86 g cm$^{-3}$. The profile depths were characterized by high sand contents and high bulk density with an increasing pattern with depth for both physical parameters. An inverse relationship was found for water holding capacity with values ranging for 0.27 cm$^3$ cm$^{-3}$ in the surface depth to 0.21 cm$^3$ cm$^{-3}$ in the 135-150 cm depth.

The CHAIN_IR model (Zhang, 1997) can solve 2-dimensional (flood) and 3-dimensional axisymmetric (drip) problems for water flow and solute transport by utilizing the Galerkin-type linear finite element schemes. The flow transport for 2-dimensional plane symmetry (flood) was determined by Richards’ equation :

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[ K(h) \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial z} \left[ K(h) \frac{\partial h}{\partial z} \right] - S$$

(1)
and for 3-dimensional axicylindrical symmetry (drip) by:

\[
\frac{\partial \theta}{\partial t} + \left(\frac{1}{r}\frac{\partial}{\partial r}\right)(rK(h)\frac{\partial h}{\partial r}) + \frac{\partial}{\partial z}(K(h)\frac{\partial h}{\partial z}) + \frac{\partial}{\partial z}(S) = 0
\]

(2)

where \( \theta = \) volumetric water content \((cm^3 cm^{-3})\), \( K = \) unsaturated hydraulic conductivity \((cm^d^{-1})\), \( h = \) pressure head \((cm)\), \( z = \) depth \((cm)\), \( r = \) radial coordinate \((cm)\), \( t = \) time \((day)\), \( S = \) sink term \((cm^3 cm^{-3} d^{-1})\). The sink term was added to the continuity of the soil-water flow equations (Equations 2 and 3) in order to account for water uptake by crop roots. The sink term \( S \) was calculated based on the approach proposed by Feddes et al. (1976), and was defined by the prescribed dimensionless function of soil water pressure head, \(-\alpha(h)\), and the potential water uptake rate, \( S_p \) (Simunek and van Genuchten, 1994). The \( S_p \) parameter was next computed based on the crop evapotranspiration \( ET \) and the root distribution function. The hydraulic properties can be described by the following expressions (van Genuchten, 1980):

\[
\theta(h) = \theta_s, \quad h \geq 0
\]

\[
\theta(h) = \theta_r + \left(\frac{\theta_s - \theta_r}{1 - \alpha(h)}\right), \quad h < 0
\]

(3)

\[
K(h) = K_s, \quad h \geq 0
\]

\[
K(h) = K_s\left(1 - \left(\frac{h}{S_o}\right)^{m}\right)^n, \quad h < 0
\]

(4)

where \( \theta_s \) and \( \theta_r \) = saturated and residual water contents \((cm^3 cm^{-3})\), respectively, \( K_s \) and \( K_o \) = saturated hydraulic conductivity and hydraulic conductivity function \((cm^d^{-1})\), respectively, \( S_o \) = degree of saturation, \( \alpha = \) scaling factor, \( n \) and \( m \) = parameters with \( m = 1-1/n \). The solute transport equation in a 2-dimensional porous medium is described by (Simunek and van Genuchten, 1994):

\[
\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial x}\left(D_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial z}(q(C)) - SC, \quad \frac{\partial}{\partial x}(D_x \frac{\partial C}{\partial x}) - \frac{\partial}{\partial z}(q(C)) - SC
\]

(5)

where \( C \) = soil concentration of NO$_3$ \((g cm^{-3})\), \( \theta = \) water content \((cm^3 cm^{-3})\), \( D = \) dispersion coefficient \((cm^2 d^{-1})\), \( q = \) Darcy flux \((cm^d^{-1})\), \( x = \) horizontal coordinate \((cm)\), \( z = \) depth \((cm)\), \( S = \) sink or root water uptake parameter \((cm^3 cm^{-3} d^{-1})\), and \( C_o = \) NO$_3$ concentration \((g cm^{-3})\). The dispersion coefficient \((D)\) is a function of longitudinal and transverse dispersivities \((\alpha_x \text{ and } \alpha_z\text{, respectively})\) and the molecular diffusion coefficient \((D_w)\). The \( S \) and \( C \) terms were added to the solute transport equation to account for uptake of NO$_3$ by the sugarbeet roots. The solute sink term represented the concentration of NO$_3$ \((C_o)\) in the water taken up by the roots \((S, \text{ from Equations 2 and 3})\), and thus, was a function of the soil moisture and crop ET. A similar equation can also be described for the 3-dimensional solute transport.

The simulation studies were conducted in a space domain of 0 to 25 cm \((x_{max} \text{ for flood and } r_{max} \text{ for drip})\) in the \( x \)- and \( r \)-direction and 0 to 150 cm \((z_{max})\) in the \( z \)-direction for a
period of 180 days corresponding to the sugarbeet growing season at TREC. The $r_{max}$ was set at 25cm considering symmetry of water flow around each dripper in the simulations and the 50cm interval between two drippers in the field study. At the soil surface, a constant water infiltration flux was applied to simulate drip and flood irrigation. For drip irrigation, water was delivered along $r = 0$ to 1 cm to reproduce the application through a dripper. The soil surface corresponding to $x = 1$ to 25 cm was subjected to an atmospheric- (flux-) type boundary condition (BC) to simulate water evaporation and infiltration from precipitation. For flood irrigation, water was delivered along $x = 0$ to 25 cm ($x_{max}$). The fluxes were 3.78 and 7 L h$^{-1}$ and corresponded to the flow rates delivered by the drippers and the gated pipes during our experimental study for drip and flood irrigation, respectively. The lateral boundaries were subjected to no-flow BC. Such conditions are applicable under drip irrigation, because the symmetrical flow geometry of each dripper and the equal spacing between drippers "create hydraulically independent flow cells that are isolated from one another by vertical streamlines at their boundaries" (Or, 1995). For flood irrigation, lateral flow was not considered because water was applied on the entire soil surface ($x = 0$ to $x_{max}$). Similar lateral BCs were imposed in studies described by Zhang (1997) and Simunek and van Genuchten (1994). A free-drainage BC was maintained at the bottom of the profile. Four depths, representative of the different soil properties observed in the 150-cm sugarbeet root zone, were considered in this study to account for spatial variability of the soil system (Table 1). Before experimental study, soils were analyzed for saturated hydraulic conductivity (Klute and Dirksen, 1986), and residual and saturated water contents (Klute, 1986); $\alpha$ and $n$ were determined by fitting Equations 3 and 4.

Four irrigation treatments, corresponding to 20, 35, 50, and 65% water depletion of field capacity (designated as Drip1, Drip2, Drip3, and Flood, respectively), were used for the simulations in conformity with the field experiment. For the treatment with lower water depletion (i.e., Drip 1), we maintained a higher frequency of irrigation events and a smaller quantity of water input during each application (Table 1). The other irrigation treatments used in the simulations were also identical to the ones followed during the field experiment. The water depths applied during each irrigation event were 48, 96, 137, and 187 mm for Drip1, Drip2, Drip3, and Flood, respectively. The irrigation frequency followed the opposite trend with water being applied 20 times under Drip1 but only 6 times under Flood. For the three drip treatments, the total depth of water applied throughout the growing season was identical and the difference between treatments was in the scheduling of irrigation and quantity of water input during each irrigation event. Irrigation applications started 100 days after sugarbeet planting.

In consistence with the field study, a basal nitrogen (N) application of 112 kg ha$^{-1}$ at the beginning of the growing season, followed by three more doses of 0, 56, and 112 kg ha$^{-1}$ after 100 days, were simulated for each irrigation treatment. Thus, three fertilizer application scenarios, comprising control (112 kg ha$^{-1}$), half-dose (168 kg ha$^{-1}$), and full-dose (224 kg ha$^{-1}$) and designated as F0, F1, and F2, respectively, were simulated conforming to the field experimental design (Table 1). In the model, the fertilizer was added as NO$_3$ to the complete soil surface ($x = 0$ to $x_{max}$ and $r_{max}$ for flood and drip irrigation, respectively). A zero-solute flux BC was imposed at the surface with NO$_3$ input applied as source in the first space increment. No solute flux was considered across the lateral boundaries following the reasoning described for the water flow BC. The maximum seasonal crop N uptake was considered to be 200 kg ha$^{-1}$, as noted by Cooke and Scott (1993). The solute input parameters included the longitudinal
### Table 1. Selected simulation-input parameters for the sugarbeet soils studied under different irrigation regimes (data for a 150 cm root zone are listed)*

**Soil hydraulic parameters**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>θ_r (cm³ cm⁻³)</th>
<th>θ_s (cm³ cm⁻³)</th>
<th>K_s (cm d⁻¹)</th>
<th>α (cm⁻¹)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 45</td>
<td>0.002</td>
<td>0.352</td>
<td>20.2</td>
<td>0.0174</td>
<td>1.38</td>
</tr>
<tr>
<td>45 – 90</td>
<td>0.002</td>
<td>0.323</td>
<td>27.1</td>
<td>0.0180</td>
<td>1.35</td>
</tr>
<tr>
<td>90 – 135</td>
<td>0.001</td>
<td>0.301</td>
<td>35.2</td>
<td>0.0196</td>
<td>1.42</td>
</tr>
<tr>
<td>135 – 150</td>
<td>0.001</td>
<td>0.277</td>
<td>37.1</td>
<td>0.0209</td>
<td>1.45</td>
</tr>
</tbody>
</table>

**Irrigation parameters**

<table>
<thead>
<tr>
<th>Regimes</th>
<th>F</th>
<th>WI (mm)</th>
<th>WD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drip1</td>
<td>20</td>
<td>48</td>
<td>20</td>
</tr>
<tr>
<td>Drip2</td>
<td>10</td>
<td>96</td>
<td>35</td>
</tr>
<tr>
<td>Drip3</td>
<td>7</td>
<td>137</td>
<td>50</td>
</tr>
<tr>
<td>Flood</td>
<td>6</td>
<td>187</td>
<td>65</td>
</tr>
</tbody>
</table>

**Fertilizer N treatments**

<table>
<thead>
<tr>
<th>F₀</th>
<th>F₁</th>
<th>F₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>168</td>
<td>224</td>
</tr>
</tbody>
</table>

* θ_r = residual water content, θ_s = saturated water content, K_s = saturated hydraulic conductivity, α = coefficient in soil water retention function (see Equations 3 and 4), n = exponent in soil water retention function (see Equations 3 and 4), F = frequency of irrigation events during the growing season, WI = water input during each irrigation application, WD = water depletion from field capacity.

Residual soil NO₃ (RSN) in the root zone and yield indices obtained from the field experiment at the end of sugarbeet growing season were compared with the related parameters predicted by our simulations. Yield ratios (YR) for sugarbeet production were calculated as:

\[ YR = \frac{Y_a}{Y_p} \]  

[6]
where $Y_a = \text{actual seasonal yield (kg ha}^{-1})$, and $Y_p = \text{potential maximum yield (kg ha}^{-1})$. We estimated different yield ratios based on the predicted sugarbeet N-uptake from simulations, as well as field experimental data for sugarbeet yield, sugar content and sugarbeet N-uptake at the end of the growing season. The potential maximum yield for sugarbeets in the TREC area was obtained from Wyoming Agricultural Statistics Service (1998). Similar representation of crop production functions has also been cited by Russo (1986).

Results and Discussion

The soil hydraulic parameters, corresponding to those observed at TREC, are listed in Table 1. The soils were characterized by low residual water content (0.002-0.001 cm$^{-3}$ cm$^{-3}$), and moderate levels of saturated water content (0.352-0.277 cm$^{-3}$ cm$^{-3}$), saturated hydraulic conductivity (20.2-37.1 cm d$^{-1}$), $\alpha$ (0.0174-0.0209 cm$^{-1}$) and $n$ (1.38-1.45). Residual and saturated water contents decreased with depth, whereas saturated hydraulic conductivity, $\alpha$, and $n$ increased. This trend was explained by the increase in coarseness with depth of the soil profile (Table 1). Periodic soil NO$_3$ levels (F$_0$ treatment) under different irrigation regimes after the first water application are shown in Figure 1. The concentrations decreased curvilinearly for all irrigation treatments, with NO$_3$ level at any given time being in the order of Drip1 > Drip2 > Drip3 >> Flood (Figure 1a). Relatively higher NO$_3$ under drip irrigation indicated less solute loss and possibly greater plant-availability of NO$_3$ in the root zone. The NO$_3$ patterns for the three drip regimes were similar with values being higher for Drip1. A more detailed comparison of soil NO$_3$ among these treatments at any specific time revealed that the solute concentration in the root zone was dependent on the frequency of irrigation and amount of water applied during each irrigation event. The higher irrigation frequency with minimal quantity of water corresponding to the least depletion percentage (Drip1) was found to be the best scheduling scheme for retaining NO$_3$ in soils as compared to the other regimes. The marked decrease in NO$_3$ concentrations with flood irrigation suggested a greater solute loss from the root zone; this was probably caused by the large quantity of water triggering higher flushing effect and subsequent leaching of NO$_3$. With progression of the growing season, NO$_3$ levels in the root zone decreased for all irrigation regimes. Soil moisture levels followed the same trend whereas crop ET rates increased with time. Lower solute concentrations were noted at higher ET values. The NO$_3$ depletion was concurrent with the soil moisture depletion from the root zone.

The trend in NO$_3$ distribution was further evident by comparing the concentration-depth gradients of each irrigation method with time (Figure 1b). The gradients at different time intervals were calculated as the rates of NO$_3$ concentration changes with depth. Throughout the irrigation period, higher (an average of 5 times) gradients were noted based on the simulations for all three drip regimes when compared to flood irrigation, which further illustrated the lower NO$_3$ loss with drip practices at any profile-depth. The concentration-depth gradient remained the highest for Drip1 throughout the whole irrigation period followed by Drip2, Drip3, and Flood regimes. This also indicated greatest efficacy with Drip1 in regard to lower soil NO$_3$ loss and higher availability to plants. Similar trends were also observed for $F_1$ and $F_2$.

Comparative NO$_3$ movement from F$_0$ treatment simulations, calculated based on first order kinetics, indicated that the rate of NO$_3$ leaching under flood irrigation was 2 to 3.5 times greater than with the three drip regimes, as suggested by the rate constant ($k$)
Figure 1. Soil NO$_3$ levels under different irrigation regimes predicted by simulations: (a) concentration (C) change in the root zone of 150 cm, and (b) variation in concentration–depth gradient (dC/dz) with time (t); results of F$_0$ fertilizer treatment are presented; error bars correspond to confidence intervals at 0.05 level.

values (Table 2). Among the three drip regimes, Drip3 had the highest NO$_3$ leaching rate that was about 1.2 and 1.5 times greater than the rates under Drip1 and Drip2, respectively. Slower leaching for Drip1 was an indication of longer residence phase of NO$_3$ in soils during the growing season. This was also evident based on the trend in half-life period $t_{1/2}$ of NO$_3$ following the order of Drip1>Drip2>Drip3>Flood (Table 2). The $t_{1/2}$ was calculated as the time required for soil NO$_3$ concentration at any profile point to decrease by 50%. Thus, as compared to flood irrigation, NO$_3$ half-lives were nearly 3.5, 2.5, and 2.0 times higher under Drip1, Drip2, and Drip3, respectively. Greater $t_{1/2}$ and less leaching of NO$_3$ under Drip1 was probably due to smaller volumes of water input during each irrigation application and the higher irrigation frequency as compared to the other regimes. The correlation coefficients for all these calculations were significantly high at $P < 0.05$.

<table>
<thead>
<tr>
<th>Irrigation</th>
<th>$k \times 10^{-3}$ ($x10^{-3}$) day$^{-1}$</th>
<th>$t_{1/2}$ day</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drip1</td>
<td>4.97</td>
<td>139</td>
<td>0.81</td>
</tr>
<tr>
<td>Drip2</td>
<td>6.82</td>
<td>102</td>
<td>0.87</td>
</tr>
<tr>
<td>Drip3</td>
<td>8.36</td>
<td>83</td>
<td>0.88</td>
</tr>
<tr>
<td>Flood</td>
<td>17.2</td>
<td>40</td>
<td>0.97</td>
</tr>
</tbody>
</table>

* $k =$ NO$_3$ leaching rate constant, $t_{1/2} =$ NO$_3$ half-life period, $r =$ correlation coefficient.

Table 2. Kinetic parameters for NO$_3$ movement predicted in sugarbeet soils under different irrigation regimes (significant at $P < 0.05$)*

A comparison of the residual soil NO$_3$ (RSN) in the root zone at the end of the growing season, predicted by the simulation, indicated the order of Drip1 > Drip2 > Drip3 > Flood.
for all three fertilizer applications (Figure 2). Concentrations of soil NO₃ under drip regimes were predicted to be about 2 to 2.5 times higher than with flood irrigation. For all four irrigation regimes, predicted RSN values also increased with increasing fertilizer levels. For each fertilizer treatment, higher RSN values under drip irrigation suggested less soil NO₃ depletion as compared to flood, and greater availability as basal dose for the following crop (for example, winter wheat) after sugarbeet. This was consistent with the irrigation management study of Geleta et al. (1994) who observed lower NO₃ leaching under drip irrigation than with flood irrigation.

Figure 2. Simulation predicted residual soil NO₃ in the root zone at the end of the growing season under different irrigation regimes and fertilizer levels; error bars correspond to confidence intervals at 0.05 level.

Assessment of simulation results with respect to field experimental data is shown in Figure 3. Soil NO₃ concentrations in the root zone corresponding to the full-dose fertilizer treatment (F₂) were analyzed at the end of the growing season, and compared to the results predicted by the computer simulations with the same fertilizer and water inputs (Figure 3a). Greater soil NO₃ concentrations under drip irrigation were observed than with the flood irrigation practices. Comparison between the data obtained from simulation and field studies showed no significant difference at P ≤ 0.05. This suggested that the simulation results could be utilized to understand in situ behavior of NO₃, which would be otherwise difficult or expensive to determine directly under variable field conditions.

The importance of using simulations for predicting the behavior of NO₃ in sugarbeet production was also determined by evaluating the yield ratios calculated from field experimental data (based on sugarbeet yield, sugar content, sugarbeet N-uptake) and simulation results (from sugarbeet N-uptake) under drip irrigation (Figure 3b). For different fertilizer applications, all four yield ratios (0.6-0.8) were comparable (at P ≤ 0.05), suggesting that the simulation-predicted sugarbeet N-uptake could be utilized for computing yield indices. Similar approach of using crop production function as yield index was also noted by Russo (1986). A yield ratio of unity indicated that the actual seasonal yield was equal to the maximum possible yield estimated from the field conditions and literature (Cooke and Scott, 1993; Wyoming Agricultural Statistics Service, 1998). For all four parameters, there was a nominal increase in yield ratios with
increasing fertilizer levels. The ratios from sugarbeet yield and sugar content were slightly higher than the ratios based on sugarbeet N-uptake.

Figure 3. Comparison of simulation results and field experimental data at the end of growing season: (a) soil NO$_3$ concentrations in the root zone for full-dose fertilizer (F$_2$) treatment, (b) yield ratios for sugarbeet under drip irrigation practices (average of three regimes); error bars correspond to confidence intervals at 0.05 level

Conclusions

In this study we compared drip and flood irrigation using computer simulations for predicting NO$_3$ movement in soils and yield indices. The simulation results were also compared with experimental field data. Less NO$_3$ loss from the root zone was observed with drip irrigation than flood practices. With drip applications, NO$_3$ had a slower movement rate and greater half-life than under flood irrigation. Slower leaching under drip treatments was an indication of longer residence phase of NO$_3$ in soils during the growing season. The residual soil NO$_3$ predicted in the root zone at the end of growing season, was higher with drip irrigation when compared to flood. Reduced loss, greater half-life period, and higher residual content of soil NO$_3$ under drip irrigation, in comparison to flood irrigation, suggested the former to be a more environmentally viable practice. Simulation results were comparable with actual data on soil NO$_3$ content and yield ratios obtained from field experiments (at P < 0.05). This suggested computer simulations could be utilized to understand natural scenarios involving crop-soil-water relationships.

References


