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Evaluation of fertigation scheduling for sugarcane using a vadose zone flow and transport model

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ABSTRACT

Micro-irrigation has become an optimal means for providing water and nutrients to crops. There is an ample space for improving fertilizer use efficiency with micro-irrigation, if the movement and reactions of fertilizers in the soil are well understood. However, the rhizosphere dynamics of nutrients is very complex, depending on many factors such as soil temperature, pH, water content, and soil and plant characteristics. Many factors cannot be easily accurately quantified. However, using state-of-the-art modelling techniques, useful and reliable information can be derived.

An attempt was made to evaluate the reactive transport of urea in the root zone of a sugarcane crop under drip irrigation, and to quantify the fluxes of urea, ammonium, and nitrate into the crop roots, volatilization fluxes, and deep drainage using a numerical model. This quantification helped in designing an optimal fertigation schedule. Various parameters used in the model were taken from either the literature or the field study. A typical scenario, based on the recommended total quantity of urea for sugar cane crop under drip irrigation in India, was tested using HYDRUS-2D. The total amount of urea was divided into fortnightly doses, depending on the stage of crop growth. For this scenario, the modelled crop uptake was found to be 30% higher than the crop demand. Consequently, an optimal fertigation schedule was developed that reduced the use of urea by 30% while at the same time providing enough N for its assimilation at all stages of crop growth. This type of modelling study should be used before planning field experiments for designing optimal fertigation schedules.

1. Introduction

Micro-irrigation has become an optimal means for providing water and nutrients to crops. In countries where the cost of water is very low, such as India, the adoption of micro-irrigation has initially been very slow. Recently however, drip irrigation combined with fertigation has been found to benefit farmers because of the very high efficiency of fertilizer use for such irrigation schemes. There is an ample scope for improving the efficiency of fertilizer use through fertigation, if the movement and reactions of fertilizers in the soil are well understood.

Simple conventional fertilizers containing nitrogen, phosphorous, and/or potassium can be applied using drip irrigation if they are soluble in water. Due to the lower solubility of phosphate fertilizers, the practice of using fertigation for phosphorous is less common. Potash fertilizers are better soluble than phosphorous, and therefore farmers use fertigation for potash fertilizers to some extent. The chief source of nitrogenous fertilizers is urea. Urea is quite soluble in water, and thus fertigation with urea is very popular among farmers. Urea is a highly reactive fertilizer and begins reacting immediately after its dissolution in water. First, urea is nitrified into ammonium, and subsequently, into nitrate (Fig. 1). While urea is electrically neutral, ammonium ions are positively charged and hence adsorb to the negatively charged clay particles well. Consequently, the leaching of ammonium ions from the soil is significantly reduced. In the soil, ammonium is converted into nitrate, which is a negatively charged ion. Therefore, nitrate does not adsorb to clay particles and hence the possibility of nitrate leaching to groundwater is very high. Plant roots absorb nitrogen in all three nitrogen forms: urea, ammonium, and nitrate. Some quantity of ammonium also gets volatilized into ammonia gas. Ammonia volatilization is highly dependent on soil pH and soil wetness. Under anaerobic conditions, nitrate can also be denitrified into nitrous oxide. However, in the case of drip irrigation, the process of denitrification can be neglected, because most of the time soil is not under saturation.

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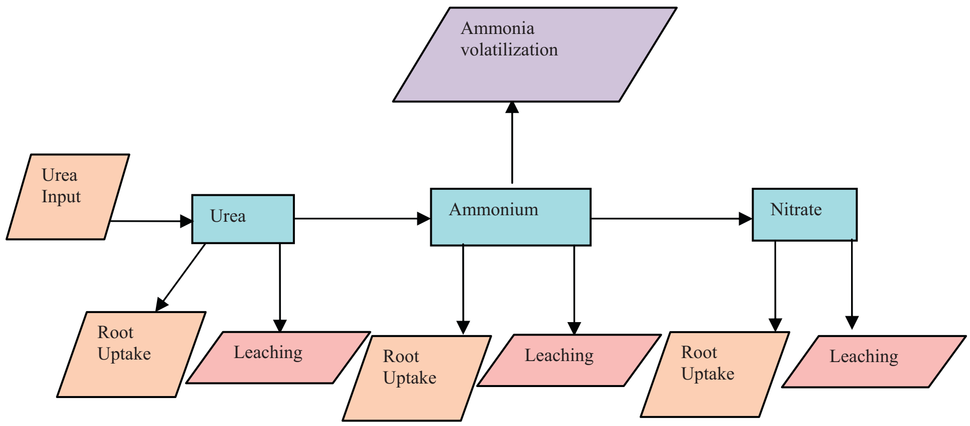

Fig. 1. Urea transformations and fate in soils.

Fertigation scheduling is the amount of fertilizer to be applied at any point in time so that before the next fertigation the plant has been able to assimilate a sufficient quantity of the fertilizer. Fig. 2 shows a typical cumulative N assimilation by plants with respect to days after planting. For instance, let us assume that during the time period between t_1 and t_2, sugarcane plants in an area assimilates 20 kg/ha of nitrogen. Let us also assume that during this time period, one can expect 4 kg/ha of volatilization loss and 1 kg/ha of deep drainage loss. If, in this situation, 25 kg/ha of nitrogen is applied at time t_1, 20 kg/ha of nitrogen will be available for the plant in the root zone. This method of applying fertilizers is called a “growth curve nutrition approach”. Butler et al. (2002) have adopted a growth curve nutrition approach for fertigation scheduling for sugarcane. One disadvantage of this approach is that it does not take into account the carry-over of a nutrient from previous periods. Additionally, for the situation discussed above, the spatial and temporal distribution of urea, ammonium, and nitrate may be such that less than 25 kg/ha of nitrogen can be taken up by the roots. Therefore, a certain quantity of excess nitrogen must be applied in order to provide sufficient amount of nitrogen to meet assimilation requirements.

Numerical simulations of water flow and urea-ammonium-nitrate reactions and transport in the vadose zone, while accounting for root water and nutrient uptake, can help in understanding of the dynamic processes in the vadose zone. Specifically, it would be possible to account for the carry-over of nutrients from previous periods to the current fertigation period. Such a modelling study could lead to an optimal scheduling of nutrient applications for any time period. This is the motivation for the present work.

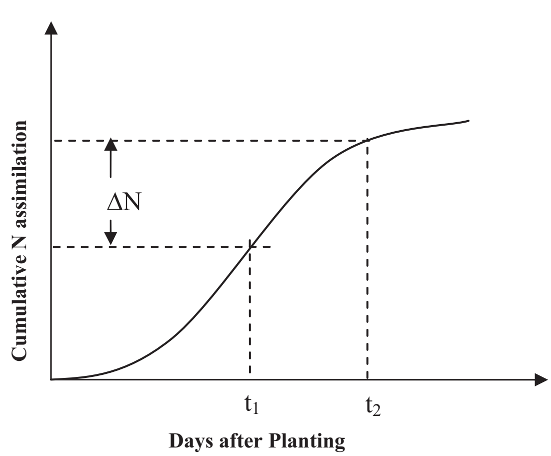

Fig. 2. A typical N assimilation curve.

Extensive field experiments were conducted to understand the mechanisms involved in the movement and transformations of various nitrogen forms and to improve the fertigation strategies by, for example, Thorburn et al. (2003), Li et al. (2004), and Rajput and Patel (2006). On the other hand, Heinen (2001) demonstrated numerically using the FUSSIM2 model that the number of fertigation treatments could be significantly reduced when planning the fertigation experiments. Similarly, HYDRUS-2D (Šimůnek et al., 2006) has been used extensively for evaluating short term nitrogen fertigation strategies and the effects of soil hydraulic properties, soil layering, dripper discharge rates, irrigation frequency, and timing of nutrient applications on wetting patterns and solute distribution (e.g., Cote et al., 2003; Gärdenäs et al., 2005; Ajdary et al., 2007; Patel and Rajput, 2008). Hanson et al. (2006) also used HYDRUS-2D for developing short term fertigation strategies while accounting for transformations of urea in soil. Additionally, Mmolawa and Or (2003) developed a semi-analytical model for predicting the movement of nitrates under plant uptake conditions. They compared the results of their semi-analytical model with the HYDRUS-2D model and with the field data and concluded that both models performed well. Finally, Šimůnek et al. (2008) provided a long list of references, in which HYDRUS had been validated for drip irrigation and other applications.

Nutrient dynamics in the rhizosphere is very complex and depends on many factors, such as soil temperature, pH, water content, and soil and plant characteristics. In addition, the temporal and spatial variations of these factors are highly dynamic. Many factors cannot be accurately quantified easily. At the same time, when reviewing the literature, it becomes clear that with state-of-the-art modelling techniques, useful and reliable information can be derived about rhizosphere processes. Many of the references cited above dealt only with short term fertigation management strategies. We could not come across any literature using HYDRUS for long term fertigation scheduling. The main objective of this study is thus to develop an optimal urea fertigation schedule for a sugarcane crop grown under drip irrigation in sandy clay loam soil for a site specific climatic conditions (Coimbatore, India) using HYDRUS-2D (Šimůnek et al., 2006).

2. Materials and methods

2.1. The HYDRUS-2D software

Water flow and fertilizer movement was simulated using the HYDRUS-2D software. This software can simulate the transient two-dimensional movement of water and the transport and reactions of adsorbing nutrients in soils. The model allows for specification of root water uptake and evaporation from the soil surface. The model is capable of simulating spatial and temporal variations of water content and nutrient concentrations in the root zone. The model is further capable of accounting for transformations of urea to ammonium, ammonium to nitrate, and ammonia volatilization in soils. The present version of HYDRUS has several limitations for evaluating fertigation scheduling: the spatial distribution of roots is constant in time and their dynamic growth cannot be considered, only passive uptake of nutrients can be considered when more than one solute is simulated, and temporal variability of surface ponded radius is not accounted for (see Gärdenäs et al., 2005; Hanson et al., 2006). Active nutrient uptake can be considered only in the recent version of HYDRUS and only for one solute (Šimůnek and Hopmans, 2009), while in this study we consider three solutes simultaneously (i.e., urea, ammonium and nitrate). However, these limitations are not prohibitive for using HYDRUS to evaluate different fertigation schedules.

Sugarcane is an annual crop. The crop harvested after the first planting is called plant sugarcane. During the first harvest of the plant, the root portion of the cane is left in the soil and only the shoot portion is harvested. The new shoots then develop from the remaining root portion. These new shoots are called ratoon sugarcane and are normally harvested for two to five years. Hence, the assumption of not considering the dynamic root growth during the crop season of ratoon sugarcane may not affect the results much.

Root interception, mass flow, and diffusion are the three main processes by which nutrients are taken up by plants (e.g., Šimůnek and Hopmans, 2009). However, Nitrogen uptake by sugarcane crop is up to 99% through mass flow (Netafim, 2011). Since most of the nitrogen uptake by sugarcane is by mass flow, the assumption of passive uptake in HYDRUS also does not represent a major constraint.

Finally, to overcome the last limitation, the average ponded surface area for a specific soil and dripper discharge rate were experimentally found and used in simulations.

2.2. Modelled transport domain and boundary conditions

The transport domain, 75 cm wide and 75 cm deep, considered in numerical simulations is shown in Fig. 3. The soil textural class in the study area is sandy clay loam. A time-variable flux boundary condition was applied at the left section of the soil surface to represent drip irrigation. This boundary condition was switched to the atmospheric boundary condition during periods without irrigation. The atmospheric boundary condition was also considered on the remainder of the soil surface. Other boundary conditions are shown in Fig. 3. The free drainage boundary was assumed to have a unit hydraulic gradient.

2.3. Coupled water flow and solute transport equations

The spatial distribution of transient water contents and pressure heads was obtained using a numerical solution of the Richards' equation:

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (K \cdot \nabla H) - S_w \quad (1)$$

where θ is the volumetric water content (cm^3/cm^3), K is the unsaturated hydraulic conductivity (cm/d), H is the hydraulic head (cm), and S_w is a sink term, accounting for plant water uptake (1/d), ∇ is the spatial gradient operator, and t is time (d).

The analytical model describing the unsaturated retention and hydraulic conductivity functions adopted in this work is the van Genuchten-Mualem model (van Genuchten, 1980), which is defined as follows:

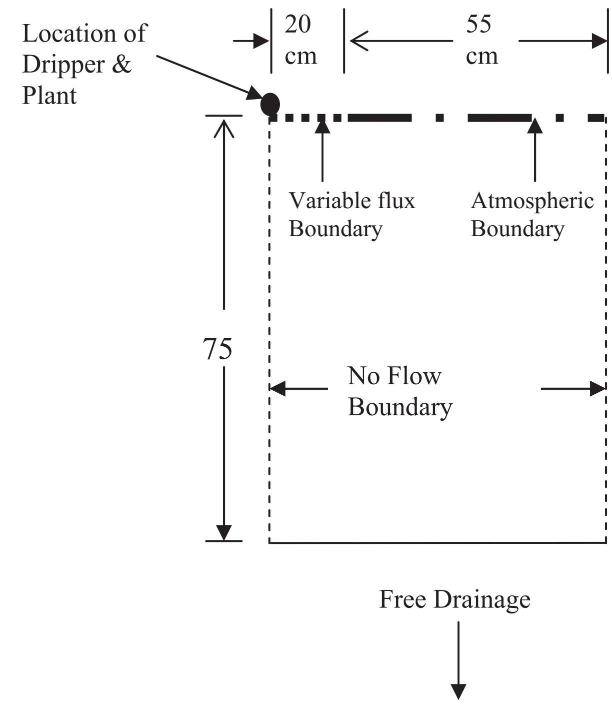

Fig. 3. Modelled transport domain and boundary conditions.

$$\begin{aligned} \theta(h) &= \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m} && \text{for } h < 0 \\ \theta(h) &= \theta_s && \text{for } h \geq 0 \end{aligned} \quad (2)$$

$$K(h) = K_s S_e^l (1 - (1 - S_e^{1/m})^m)^2 \quad (3)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (4)$$

$$m = 1 - \frac{1}{n}; \quad n > 1 \quad (5)$$

where $\theta(h)$ and $K(h)$ are volumetric water contents (cm^3/cm^3) and unsaturated hydraulic conductivities (cm/d) at the soil water pressure heads of h (cm), respectively; θ_r and θ_s denote residual and saturated water contents (cm^3/cm^3), respectively; S_e is the effective saturation, K_s is the saturated hydraulic conductivity (cm/d), α is the inverse of air-entry value or (bubbling pressure (1/cm), n is the pore size distribution index, and l is the pore connectivity parameter.

The solute transport equation solved for each chemical species is as follows:

For urea:

$$\frac{\partial \theta c_1}{\partial t} = \nabla \cdot (\theta D \nabla c_1) - \nabla \cdot (q c_1) - \mu_a \theta c_1 - S_w c_1 \quad (6)$$

For ammonium:

$$\frac{\partial \theta c_2}{\partial t} + \rho \frac{\partial s_2}{\partial t} = \nabla \cdot (\theta D \nabla c_2) - \nabla \cdot (q c_2) - \mu_v \theta c_2 - \mu_n \theta c_2 + \mu_a \theta c_1 - S_w c_2 \quad (7)$$

For nitrate:

$$\frac{\partial \theta c_3}{\partial t} = \nabla \cdot (\theta D \nabla c_3) - \nabla \cdot (q c_3) + \mu_n \theta c_2 - S_w c_3 \quad (8)$$

where c_i is the liquid phase concentration of the chemical species i (subscripts 1, 2, and 3 represent urea, ammonium, and nitrate, respectively) (g/cm^3), D is the dispersion coefficient tensor (cm^2/day), q is the volumetric flux density (cm/day), ρ is the bulk density of the soil (g/cm^3), s_2 is the adsorbed concentration of ammonium (g/g), μ_a is the first-order reaction rate constant (1/d) representing nitrification of urea to ammonium, μ_v is the first-order reaction rate constant (1/d) representing volatilization of ammonium to ammonia and μ_n is the first-order reaction rate constant (1/d) representing nitrification of ammonium to nitrate.

The relationship between ammonium in solution (c_2) and adsorbed (s_2) is described as follows:

$$S_2 = K_d c_2 \tag{9}$$

where K_d is the distribution coefficient for ammonium (cm^3/g).

The dispersion tensor has the following components:

$$\begin{aligned}
\theta D_{xx} &= \varepsilon_L \frac{q_x^2}{|q|} + \varepsilon_T \frac{q_z^2}{|q|} + \theta \tau D_0 \\
\theta D_{zz} &= \varepsilon_L \frac{q_z^2}{|q|} + \varepsilon_T \frac{q_x^2}{|q|} + \theta \tau D_0 \\
\theta D_{xz} &= (\varepsilon_L - \varepsilon_T) \frac{q_x q_z}{|q|}
\end{aligned} \tag{10}$$

where $|q|$ is the absolute value of the volumetric flux density (cm/d), q_x and q_z are the volumetric flux densities in x and z directions (cm/d), ε_L and ε_T are the longitudinal and transverse dispersivities (cm), respectively, D_0 is the coefficient of the molecular diffusion for solute in free water (cm^2/d), and τ is the tortuosity factor. The longitudinal dispersivity along the direction of flow is taken as 5 cm and the transverse dispersivity is taken as 0.5 cm. Molecular diffusion is neglected.

Eqs. (1), (6), (7), and (8) are coupled equations that are solved sequentially. Solution of Eq. (1) provides the spatial and temporal distributions of water content (θ). The root uptake term (S_w) is also obtained when solving Eq. (1). The reaction rate constants (μ_a, μ_v, and μ_n) and the distribution coefficient for ammonium (K_d) are concentration independent and hence Eq. (6) through (8) are linear equations. When solving Eqs. (6) through (8), the distribution of θ and S_w is known and the unknowns are the solute concentrations, namely concentrations of urea (c_1), ammonium (c_2), and nitrate (c_3), respectively. The first-order reaction term representing nitrification of urea to ammonium (μ_a) acts as sink in Eq. (6) and as source in Eq. (7). Similarly, the first-order reaction term representing nitrification of ammonium to nitrate (μ_n) acts as sink in Eq. (7) and as source in Eq. (8). The last terms in Eqs. (6) through (8) are the products of root water uptake (S_w) and concentrations of respective species, and hence represent the passive uptake of urea, ammonium, and nitrate, respectively.

2.4. Estimation of evaporation and transpiration

Calculations are carried out for Coimbatore, in the western part of the southernmost state of India Tamil Nadu. The geographic location of Coimbatore is 11°01′N and 76°58′E and has an altitude of about 398 m. Coimbatore has a tropical wet and dry climate. It gets most rainfall during two monsoons. The South West monsoon comes from June to August. After a warm, humid September, the North East monsoon comes from October till early December. The average annual rainfall is around 700 mm, with the South West and North East monsoons contributing 28 and 47%, respectively, to the total rainfall. Fig. 4 provides monthly climatic variations at Coimbatore.

HYDRUS needs as input potential evaporation from the soil surface and potential transpiration through plants. Both evaporation from the soil surface and transpiration by plants were calculated on a daily basis using the dual crop coefficient approach of Allen et al. (1998). In the dual crop coefficient approach, the evapotranspiration of the crop (ET_c) is estimated using the following equation:

$$ET_c = (K_{cb} + K_e) \times ET_o \tag{11}$$

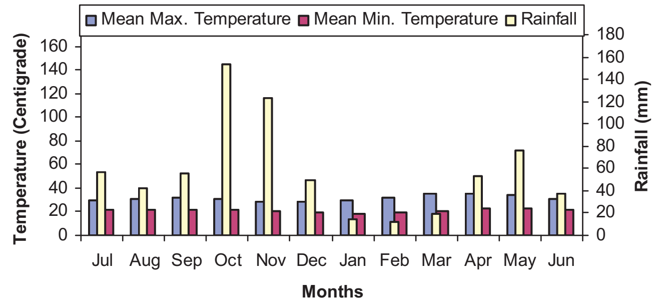

Fig. 4. Monthly climate data at Coimbatore, India.

where K_{cb} is the basal coefficient, K_e the evaporation coefficient, and ET_o is the reference crop evapotranspiration computed using the Penman–Monteith combination equation using the relevant meteorological data and the ET_o calculator (Raes, 2009). The K_{cb} is defined as the ratio of ET_c to the ET_o when the soil evaporation is zero and the soil surface is dry and the transpiration component is fully met by sufficient water available in the root zone below the soil surface (Allen et al., 1998). The K_{cb} component also includes the diffusive evaporative water movement from the root zone below the surface. The soil evaporation coefficient (K_e) describes the evaporation component from the soil surface. If the soil is wet following a rain or irrigation, the value of K_e may be large. The sum of K_e and K_{cb} can never exceed a maximum value (K_{cmax}) determined by the energy available for evapotranspiration. More details about how to evaluate these coefficients can be found in Allen et al. (1998).

Values of the basal crop coefficient (K_{cb}) used for different stages of crop are as follows: for the initial 30 days, K_{cb} is equal to 0.15, for the next 50 days during the development stage, the K_{cb} linearly varies from 0.15 to 1.2, for the next 180 days of mid stage, the K_{cb} is constant with a value of 1.2, and for the final 60 days, the K_{cb} linearly varies from 1.2 to 0.7 (Allen et al., 1998).

It was assumed that irrigation was applied when the cumulative sum of evaporation and transpiration in the wetted fraction of soil exceeded 10 mm during the first 30 days and 20 mm thereafter. A constant irrigation depth of 7.5 mm was maintained throughout the entire season. The irrigation interval varied from 2 to 3 days on non-rainy days and longer during rainy days. 58 irrigation events took place during the growth season (Fig. 5).

It was also assumed that the crop was planted on July 1st, 2008. Daily values of transpiration and evaporation were calculated for 230 days using the procedure outlined above (Fig. 5). The total crop evapotranspiration during 230 days was 861 mm and the total irrigation was 435 mm. The balance of 426 mm was met by the rainfall.

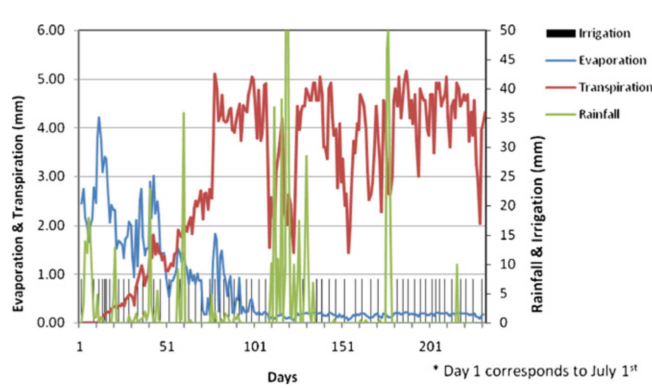

Fig. 5. Evaporation, transpiration, irrigation and rainfall during 230 days of simulation (note: different scales on two vertical axes).

Table 1
Fertigation days and urea doses for different fertigation scenarios.

Fortnightly periods	Fertigation day	Fertigation amount of urea (kg/ha)		
		Scenario 1	Scenario 2 (simple balancing)	Scenario 3 (with carry-over from previous time periods)
1	1[a]	30	1.8	2
2	15	35	12.7	15
3	28	40	14.5	15
4	42	45	21.7	22
5	57	45	21.7	22
6	74	45	25.4	25
7	88	45	47.1	70
8	102	45	54.3	70
9	116	30	54.3	70
10	135	30	47.1	70
11	146	30	43.5	19
12	161	30	29.0	–
13	181	30	25.4	–
14	197	30	25.4	–
15	212	30	10.9	–
Total		540	435	400

[a] The first day corresponds to 1 July.

2.5. Root water uptake

The sink term, S_w, in Eq. (1), and (6)–(8), represents the volume of water removed per unit time from a unit volume of soil due to plant water uptake. The water stress is accounted for using the model suggested by Feddes et al. (1978), which is implemented in HYDRUS:

$$S_w(h) = \alpha(h) S_p \tag{12}$$

where h is the soil water pressure head (cm), $\alpha(h)$ is the water stress response function, which varies between 0 and 1, and S_p is the potential root water uptake rate (1/d). Fig. 6 gives a schematic plot of the stress response function as used by Feddes et al. (1978). The values of limiting pressure heads used in this work are as follows: $h_1 = -10$ cm; $h_2 = -25$ cm; $h_3 = -1000$ cm; $h_4 = -8000$ cm.

The potential root water uptake rate is non-uniformly distributed within the root zone:

$$S_p = b(x, z) S_t T_p \tag{13}$$

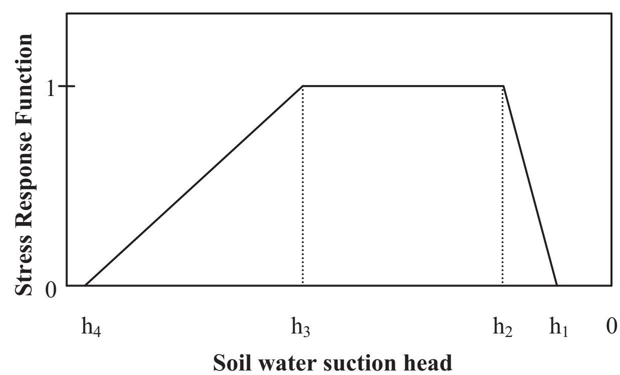

Fig. 6. Stress response function according to Feddes et al. (1978).

where $b(x,z)$ is the normalized root water uptake distribution in the vertical x–z plane (1/cm^2), S_t is the length of the soil surface associated with the transpiration (cm), and T_p is the potential transpiration rate (cm/d). HYDRUS distributes the root water uptake

Table 2
Nitrogen concentrations in irrigation water.

15 day periods (1)	Urea applied (Scenario 1) (kg/ha) (2)	Urea applied (mmol/ha) Col(2)/0.06[a] × 1000 (3)	Nitrogen (N) (mmol/ha) Col(3) × 2[b] (4)	N per cm of lateral (one side) mmol per cm length of lateral Col(4)/1333333[c] (5)	N concentration (mmol/cm^3) Col(5)/16.667[d] (6)
1	30	500,000	1,000,000	0.750	0.0450
2	35	583,333	1,166,667	0.875	0.0525
3	40	666,666	1,333,333	1.000	0.0600
4	45	750,000	1,500,000	1.125	0.0675
5	45	750,000	1,500,000	1.125	0.0675
6	45	750,000	1,500,000	1.125	0.0675
7	45	750,000	1,500,000	1.125	0.0675
8	45	750,000	1,500,000	1.125	0.0675
9	30	500,000	1,000,000	0.750	0.0450
10	30	500,000	1,000,000	0.750	0.0450
11	30	500,000	1,000,000	0.750	0.0450
12	30	500,000	1,000,000	0.750	0.0450
13	30	500,000	1,000,000	0.750	0.0450
14	30	500,000	1,000,000	0.750	0.0450
15	30	500,000	1,000,000	0.750	0.0450

[a] One mmol of urea = 0.06 g.
[b] 2 atoms of nitrogen exist for every molecule of urea.
[c] Spacing between crop rows is taken as 1.5 m. Therefore, 666,666 cm length of laterals exist in one hectare; for one side of a lateral, it is again divided by 2.
[d] Fertigation is performed during 1 h.
Discharge for 1 h for one side of a lateral per cm length = 16.667 cm^3/cm.

Table 3
Nitrogen balance for 230 days of simulation obtained using HYDRUS.

No.	Process	Cumulative nitrogen (kg/ha)		
		Scenario 1	Scenario 2	Scenario 3
1	Urea applied	257.14	184.80	170.43
2	Root uptake of urea	26.74	24.66	22.40
3	Root uptake of ammonium	29.41	24.63	25.01
4	Root uptake of nitrate	101.42	74.46	79.52
5	Volatilization of ammonium	32.11	24.17	24.83
6	Leaching of nitrate	11.852	3.72	4.11
7	Leaching of ammonium and urea	Insignificant	Insignificant	Insignificant
8	Nitrogen left in the soil after 230 days	55.61	33.14	14.55

according to Vrugt et al. (2001):

$$b(x,z) = \left(1-\frac{x}{x_m}\right)\left(1-\frac{z}{z_m}\right)e^{-\left(\frac{p_x}{X_m}|X^*-X|+\frac{p_z}{Z_m}|Z^*-Z|\right)} \quad (14)$$

In this equation, the origin is taken at the location of the plant, z_m and x_m are the maximum width and depth of the root zone (cm), respectively, z^* and x^* are the locations of the maximum root water uptake in vertical and horizontal directions (cm), respectively, and the p_x and p_z values are taken to be equal to one except for $x > x^*$ and $z > z^*$ when they become zero.

2.6. Irrigation and fertigation

For HYDRUS, the data must be given in terms of depth of water applied on the time-variable flux boundary. The duration of irrigation is considered 3 h and 15 min for each irrigation event. The fertigation strategy involved applying fresh water for the first 2 h, fertilizer with irrigation water for the next 1 h, and fresh water again for the last 15 min to flush the lines. The first fertigation event took place on the first day of planting (July, 1st). The subsequent fertigation events were adjusted to the irrigation events with a fertigation interval of approximately 15 days (Table 1). The N assimilation data for the ratoon sugarcane plant for the CB41-76 variety (Netafim, 2011) is as follows: 40 kg/ha during the first 4 months, 95 kg/ha during the following 2 months, and 120 kg/ha for the last 2 months.

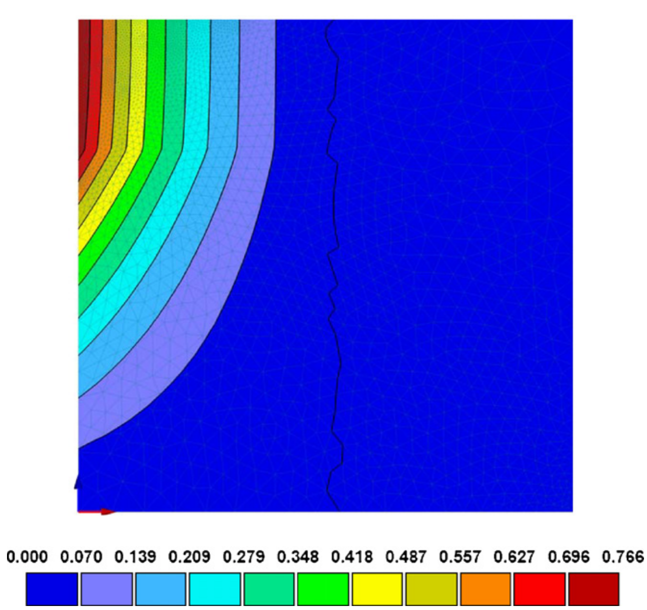

Fig. 7. Distribution of root water uptake function.

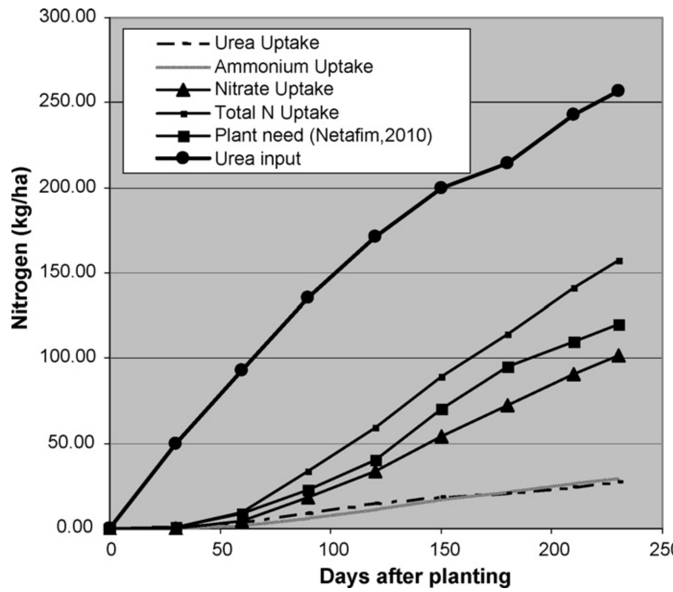

Fig. 8. Comparison of root uptake of nitrogen simulated using HYDRUS with the nitrogen requirement by sugarcane.

A recommendation of 540 kg/ha of urea, provided by the Jain Irrigation System, Ltd. (http://jains.com/), is examined first. This is a typical recommendation followed by many farmers in India. The application of 540 kg/ha of urea was divided into fortnightly intervals according to the growth stage (Table 2). Different columns of Table 2 illustrate the procedure adopted to calculate concentrations

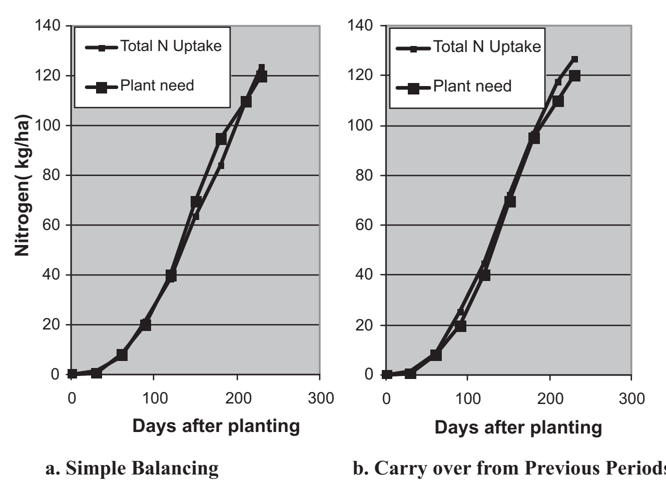

Fig. 9. Root nitrogen uptake for scenarios matching plant uptake with fertigation doses.

of N in irrigation water for a single dripper step by step. This approach is referred to below as Scenario 1.

Based on the simulated results obtained in Scenario 1, two types of modifications of this policy were done. The results of Scenario 1 provide the overall nitrogen uptake efficiency. Fortnightly (two weeks) urea requirements can be evaluated by using the N assimilation data for different stages of the crop and the Scenario 1 nitrogen uptake efficiency. These biweekly urea requirements are referred to as Scenario 2 and called "simple balancing policy", since they are calculated only based on the plant need for a given fortnight and an assumption that the soil available N for plant uptake before fertigation is zero. In reality, the actual amount of N taken up by the plants may be either more or less than the plant need and some N may remain in the soil. Therefore, simple balancing policy of Scenario 2 is also suboptimal and its level of sub-optimality may be evaluated using HYDRUS. Scenario 2 was then modified by trial and error by adjusting fertigation doses until the simulated N uptake and the plant need match closely. The final optimal run is referred to as Scenario 3.

2.7. Input data for HYDRUS

While many of the input parameters required by HYDRUS were taken from the literature, some parameters were estimated from the field work.

2.8. Data from the literature

The soil hydraulic parameters for sandy clay loam were taken from the Rosetta Lite program (Schaap et al., 2001), which is incorporated in HYDRUS. They are as follows: the residual water content (θ_r) is 0.063, the saturated water content (θ_s) is 0.384, the saturated hydraulic conductivity (K_s) is 13.2 cm/day, the pore connectivity parameter (l) is 0.5, and the values of α and n are 0.021 cm^{-1} and 1.33, respectively.

The first-order rate constant for nitrification of urea to ammonium (μ_a) is assumed to be 0.38 per day, for nitrification of ammonium to nitrate (μ_n) 0.2 per day (Hanson et al., 2006), and for volatilization of ammonium to ammonia (μ_v) 0.0552 per day

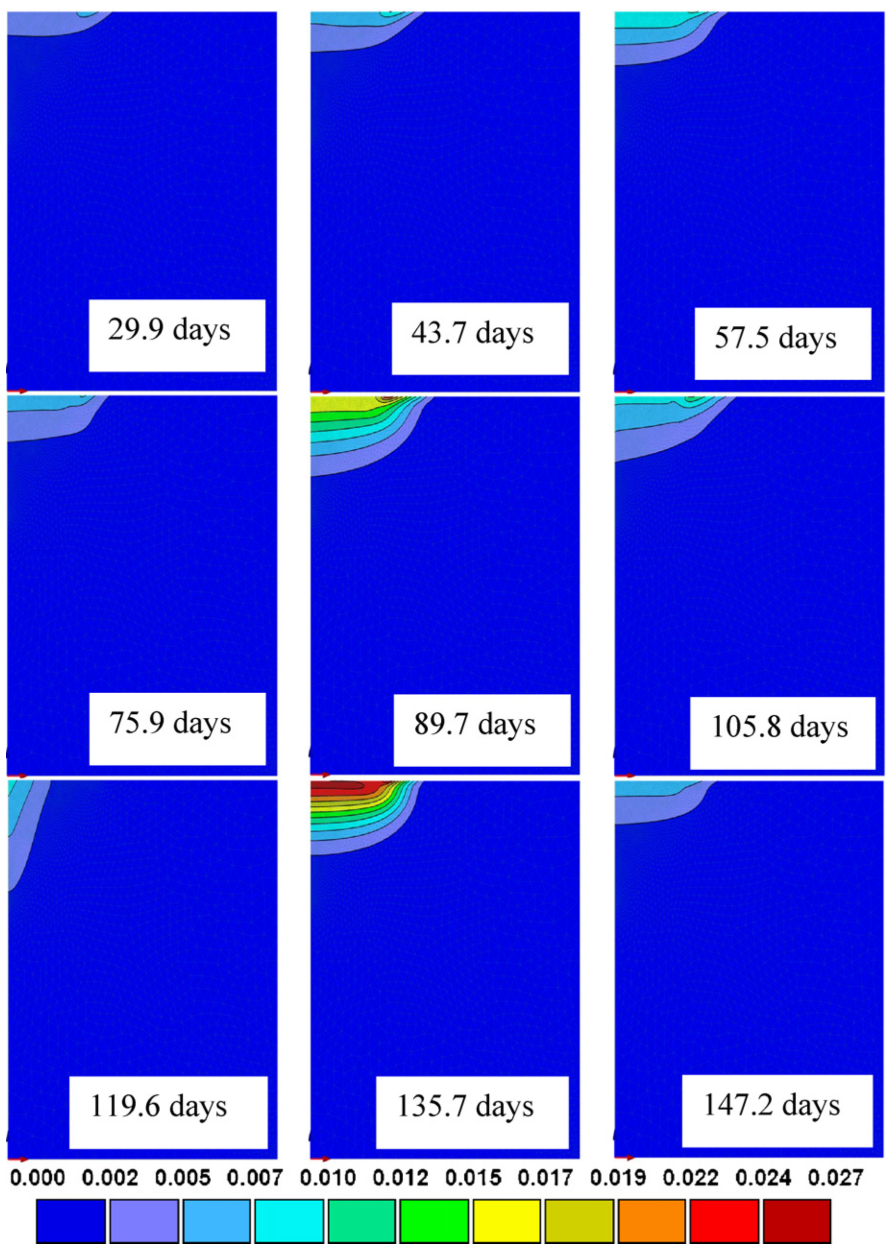

Fig. 10. Spatial distribution of urea concentrations (mmol/cm^3) for Scenario 3.

(Bolado Rodriguez et al., 2005). The distribution coefficient for ammonium (K_d) is assumed to be 3.5 cm^3/g (Hanson et al., 2006).

2.9. Data from the field work

The measured bulk density was 1.53 g/cm^3. We assumed a line source with drippers spaced at 60 cm and with each dripper having a discharge rate of 2 litres per hour (L/h). The radius of the ponded area for the 2-L/h dripper in a sandy clay loam soil was experimentally found to be 20 cm. Therefore, a 20-cm boundary length was used to represent irrigation from surface drippers. Two litres per hour per dripper at a spacing of 60 cm on a 20 cm recharge boundary leads to a flux of 20 cm^2/day per cm length of the lateral.

The root growth of the sugarcane crop was studied in the field by observing the maximum root depth and maximum root radius at regular time intervals in excavated transects. The maximum root depth (z_m) and the maximum root radius (x_m) were found to be equal to 75 and 37.5 cm, respectively. The spatial pattern of water uptake was evaluated from tensiometer measurements. Ten tensiometers were installed for this purpose at five different depths (15, 20, 25, 35, and 40 cm) below the lateral and at a distance of 15 cm from the lateral. From soil moisture depletion during one irrigation cycle, we estimated the depth (z^*) and radius (x^*) with maximum root uptake to be 20 cm and 0 cm, respectively. Fig. 7 shows the distribution of root water uptake obtained using Eq. (14) and the above-determined root parameters.

2.10. Numerical simulations

HYDRUS-2D was used to solve the flow and transport equations for specified initial and boundary conditions. Numerical simulations produced the spatial and temporal distribution of volumetric water contents, and the solution concentrations of urea, ammonium, and nitrate. The initial water content in the soil was

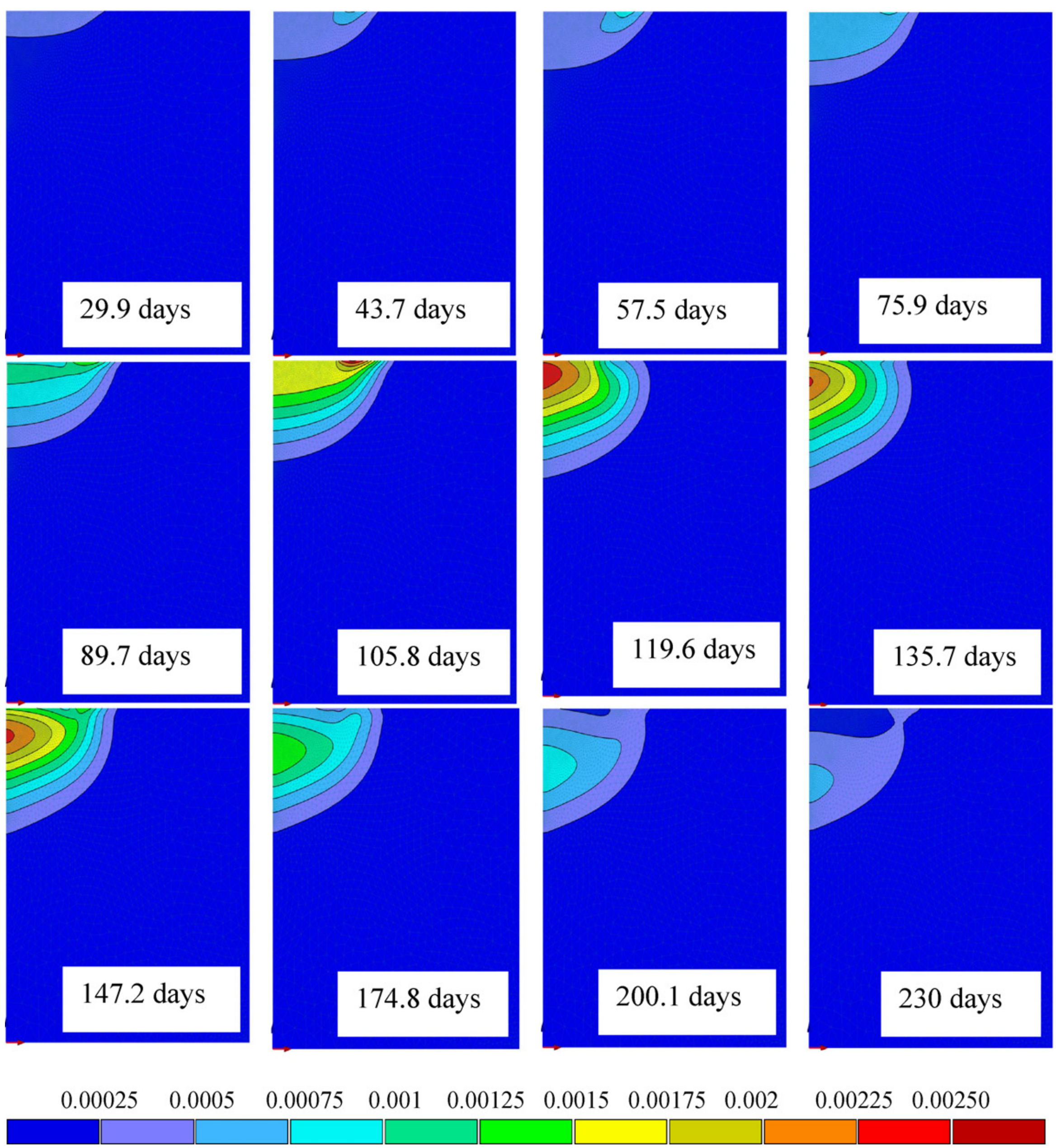

Fig. 11. Spatial distribution of ammonium concentrations (mmol/cm^3) for Scenario 3.

0.25 cm^3/cm^3, and the soil was assumed not to contain initially any residual N. The initial concentrations of urea, ammonium, and nitrate were thus assumed to be zero. Simulations were carried out for 230 days from the date of planting (July 1st).

3. Results and discussion

Table 3 shows the nitrogen balance for the 230-day simulations obtained using HYDRUS for all three scenarios. During the 230-day period for Scenario 1, 12% of N was volatilized, 5% was leached, and 61% was taken up by plant roots (the nitrogen use efficiency). Fig. 8 shows the root N uptake in all three N forms for Scenario 1. It can be seen that the total nitrogen uptake throughout the crop season is above the crop need. At the end of the 230-day time period, the crop N uptake is 30% higher than the plant N need (Netafim, 2011).

Table 3 shows that about 60% of the applied urea was taken up by plants in Scenario 1. From Table 3, it can also be observed that in Scenario 1, 55.6 kg/ha of nitrogen remained in the soil after 230 days. Though some fraction of this nitrogen may be useful for root extraction after 230 days, all this nitrogen is assumed to exist in the soil below the root zone. Scenario 2 was obtained based on the growth curve nutrition approach. The plant need for each fortnight was obtained by dividing the plant need by 0.6, as 60% of applied urea is taken up by plants. Urea doses calculated for Scenario 2 are shown in Table 1. The total amount of urea applied in Scenario 2 is 435 kg/ha. Fig. 9a shows comparison of plant demand and simulated N plant uptake for this scenario. It can also be observed that during the periods of peak N requirement, plant uptake is less than what plants need. This is because, for higher application rates, fertilizer uptake does not occur at 60% efficiency. However, it should be noted that the total nitrogen uptake at the end of the simulation period is higher than the requirement. Nevertheless, this kind of fertigation is suboptimal, as the time of N uptake does not always match the time of requirement.

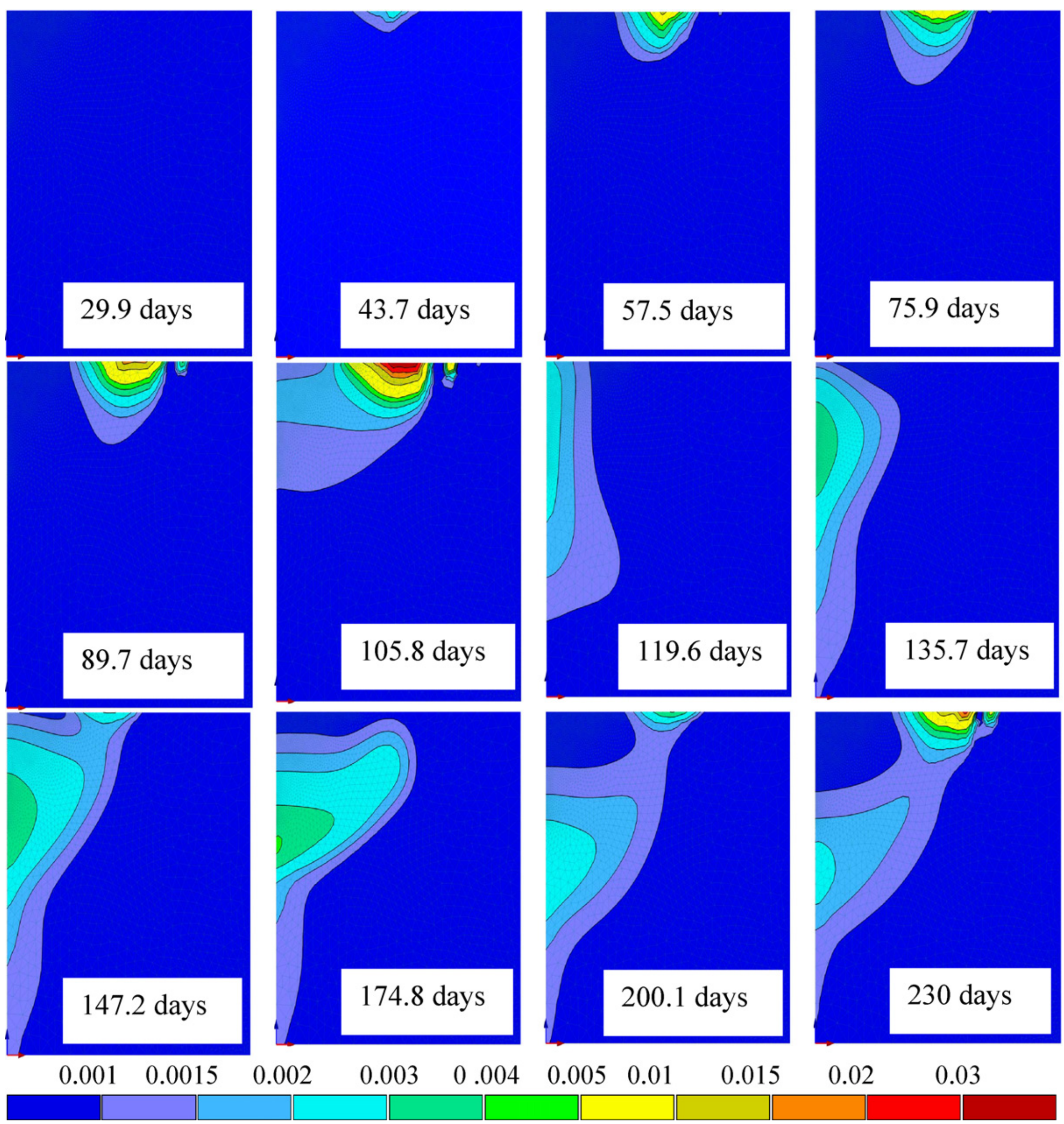

Fig. 12. Spatial distribution of nitrate concentrations (mmol/cm^3) for Scenario 3.

Scenario 3 was devised by trial and error so that the simulated plant uptake and plant needs are closely matched. The doses of urea obtained for Scenario 3 are also shown in Table 1. The total amount of urea applied for Scenario 3 is 400 kg/ha, which is 35 kg less than for Scenario 2. From Fig. 9b, it can be seen that plant uptake and crop needs closely match. There is a slightly higher uptake during the time period after 200 days. Though fertigation is stopped on the 165th day, the higher crop uptake still occurs because of the residual nitrogen remaining in the soil. This nitrogen exists in the soil because during earlier periods, more urea was applied to meet the requirements in the periods 7 through 10.

Table 1 reports the days on which fertigation occurred and the quantity of urea applied during each fertigation event. Note that fertigation events did not occur at exactly biweekly intervals, since each fertigation is associated with irregular irrigations. Fig. 10 shows the spatial distribution of urea immediately after the 3rd through 11th fertigation event for Scenario 3. Spatial distributions of urea after different fertigation events are quite similar except for the one on 119.6th day because of the rainfall that caused significant leaching.

Fig. 11 shows the spatial distribution of ammonium for Scenario 3 at the same times as in Fig. 10, with three additional times on day 174, 200, and 230. While ammonium initially builds up in the root zone until about day 147, its concentrations are subsequently reduced due to plant uptake and nitrification, without any replenishment by further fertigations. Due to its adsorption to the soil, ammonium is concentrated near the dripper.

Fig. 12 shows the spatial distribution of nitrate on the same days. Initially, till about day 90, nitrate concentrations in the root zone are relatively low since almost all nitrate is taken up by the plants. There is some build up of nitrate at the soil surface at distances beyond the root zone, because of evaporation and a lack of local root water/nutrient uptake. This process can be better understood by observing the distribution of root water uptake shown in Fig. 7. There is significant leaching of nitrate due to rain after 106 days.

4. Summary and conclusions

The rhizosphere dynamics of nutrients is very complex and depends on many factors, such as soil temperature, pH, water content, and soil and plant characteristics. Also, the temporal and spatial variations of these factors are highly dynamic. Many factors cannot easily be accurately quantified. The objective of this work thus was to evaluate the nutrient dynamics and root uptake of nutrients by the sugarcane crop grown under drip irrigation with the state-of-the-art modelling tools and to examine whether fertigation scheduling could be optimized. An attempt has been made to better understand the reactive transport of urea in the root zone of the sugarcane crop and to quantify the flux of urea, ammonium, and nitrate into crop roots, ammonia volatilization flux, and deep drainage. This quantification helped in designing a satisfactory fertigation schedule that produced a reduction in the use of urea by 30%, while at the same time providing enough N for its assimilation at all stages of crop growth. Various parameters used in the model were taken from the literature and a few of them were taken from the accompanying field study.

Our results indicate that HYDRUS can be very helpful in improving the fertigation schedules using the growth curve nutrition approach. However, a field-scale validation will be required before this approach can be recommended to farmers. We are planning to carry out such field-scale study and will report our results in this journal once the study is concluded.

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