

Surface fertigation: a review, gaps and needs

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Abstract

Surface fertigation is a common choice when it comes to applying fertilizers in surface irrigated crops. The inherent complexity of the concepts and equations governing surface fertigation has made this technique a challenging research issue in the past decades. A number of researchers have used field experiments and/or modelling results to develop recommendations aiming at improving surface fertigation management. In this paper, these recommendations are reviewed and classified considering the particular type of surface irrigation system. Key factors affecting surface fertigation performance, such as the inflow hydrograph, soil and water quality, effective root depth for fertilizer uptake and the specific surface irrigation method are discussed. The history of surface fertigation modelling is reviewed, introducing key developments, accomplishments and open issues. Finally, current research gaps and needs are identified and discussed, such as the coupling of two-dimensional surface and subsurface simulation models or the use of performance optimization approaches. Research gaps require an intensification of modelling and/or experimental efforts.

Additional key words: fertilizers; inflow hydrograph; modelling; soil and water quality; effective root depth.

Introduction

Population growth and development are resulting in an increased need for food. Consequently, the use of chemical fertilizers will continue to escalate in an attempt to increase crop yields. The annual increase rate of world fertilizer consumption in the period of 2008-2013 is 2.2% for nitrogen (N), 3.8% for phosphate (P₂O₅) and 5.3% for potash (K₂O). However, this increase is not uniformly distributed across the world (FAO, 2009). Forecasts for world-wide fertilizer consumption in 2013 and 2016 are 184 and 194 million tons of nutrients, respectively (FAO, 2012). Meanwhile, inefficient fertilizer management has led to serious environmental and economic problems in different areas of the world; Thus, the only reasonable way to solve this problem is to improve fertilizer management (Bingham *et al.*, 1971; Adriano *et al.*, 1972; Letey *et al.*, 1977; Stark *et al.*, 1983; Sánchez *et al.*, 1994; Feinerman & Fulkovitz, 1997; Santos *et al.*, 1997; Fernández *et al.*, 1998; Zerihun *et al.*, 2003). In irrigated agriculture, one of the most practical man-

agement methods to apply fertilizers is to inject them directly into the irrigation water. This process is known as fertigation (Hagin & Lowengart, 1996). Some important advantages of fertigation in comparison with traditional fertilizer application methods include flexibility and manageability, cost-effectiveness, the potential for improved fertilizer distribution uniformity and application efficiency (which results in more uniform crop growth along the field), lower losses due to reduced osmotic pressure (low fertilizer concentration), and the possibility to split nutrients application during the growing season. Fertigation can be effectively used to control fertilizer losses and the resulting pollution risk.

The first study on fertigation was probably published by Bryan & Thomas (1958) in pressurized irrigation systems. Despite the fact that fertigation in surface irrigation systems (surface fertigation) has been a common, traditional agricultural practice, academic research about surface fertigation has been very scarce until the end of the 20th century (*e.g.* Muirhead *et al.*, 1985a,b). Scarce research developments in surface fertigation may be attributed to the frequent low efficiency of surface irrigation systems (as compared to pressurized systems) (Threadgill, 1991), to the in-

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herent complexity of the governing equations and to the decades required to develop sufficient computing capacity in personal computers (Izadi *et al.*, 1996). Most world irrigated land is under surface irrigation (USGS, 2000; FAO, 2007). As a consequence, agrochemical pollution (such as that resulting from fertilizers and pesticides) is closely linked to surface irrigation systems. In the near future, the need for further research on surface fertigation can be justified by: 1) the inaccessibility of pressurized systems in many farms around the world due to economic and social aspects; 2) the emergence of advanced computer hardware and software facilitating design and operation; 3) research reports showing that the uniformity of border and furrow irrigation can be comparable to that of pressurized systems (Kay, 1990; Hanson *et al.*, 1995), without the need for energy input above field level; and 4) the independence of fertilizer and water efficiency in many surface fertigation scenarios (Playán & Faci, 1997; Sabillón & Merkle, 2004; Adamsen *et al.*, 2005; Burguete *et al.*, 2009a).

In recent years, a number of research works on surface fertigation and related topics have been published. Some of these papers discussed the transport of solutes sprayed on the soil prior to a surface irrigation event (Izadi *et al.*, 1993, 1996; Mailhol *et al.*, 2001; Zhang *et al.*, 2010). Although the subsurface solute transfer of surface-sprayed chemicals shows similarities with surface fertigation, the solute is not injected in the irrigation water. As a consequence, solute transport in overland water is not part of the problem, and the initial and boundary conditions for solute transport in the soil are different from surface fertigation. Thus, such research works were not considered in this review. Likewise, research works comparing crop yield (quantity and/or quality) in conventional fertilization *vs.* fertigation (*e.g.* Dawelbeit & Richter, 2004) or comparing fertigation performance in surface *vs.* pressurized irrigation systems (Wang *et al.*, 1997; Dillon *et al.*, 1999; Quinones *et al.*, 2007) were not included either.

In this paper, two specific aspects of surface fertigation are reviewed. The first aspect is field experimentation and modelling. Basic procedures for field experimentation and the indices commonly used for surface fertigation performance analysis are briefly discussed. An overview of the model typologies developed for this purpose is presented in summary form, and the contributions of each modelling effort are outlined. The second aspect is surface fertigation management considerations. Key management factors are

presented, and strategies to improve fertigation management (based on experimentation or modelling) are discussed. In a final section, key research gaps and needs, and an agenda for future research developments are presented. The authors set out to provide an in-depth coverage of surface fertigation in this review. However, significant research areas and developments have necessarily received limited attention. Readers are invited to refer to the original papers for further details.

Field experimentations

Surface fertigation field experiments aim at elaborating management recommendations for increasing the uniformity/efficiency of fertilizer application or at collecting field data for the calibration and validation of mathematical models. Required field data typically include advance and recession curves, inflow and outflow hydrographs and the time evolution of overland water and soil fertilizer concentration at different stations distributed along the furrow/border/basin. In agronomic studies, crop growth, yield and components are often assessed. In these cases, the use of statistical designs oriented towards the use of ANOVA techniques is desirable to firmly assess the relationship between fertigation performance and experimental treatments. However, the large size of the experimental units (a set of irrigated furrows, a border or a basin) makes such designs very difficult to implement in practice (Ebrahimian *et al.*, 2012b). Statistically designed experiments are not known in surface fertigation. This issue remains a serious limitation to fertigation experiments, particularly if variables such as crop yield, fertilizer uptake or fertilizer leaching are to be analysed.

Surface fertigation can be performed using solid fertilizers or liquid fertilizers (Playán & Faci, 1997). Fertilizer solutions are increasingly used in both fertigation practice and scientific experimentation. In field experiments, the fertilizer solution is applied at the upstream end of the experimental field using containers equipped with regulation valves and other devices (such as injection pumps or Mariotte tubes) to maintain stable, pre-set injection rates. The injection rate is critical for the success of the experiment, and should be assessed before each experiment. Fig. 1 presents a scheme of experimental irrigation and fertigation systems for alternate furrow fertigation.

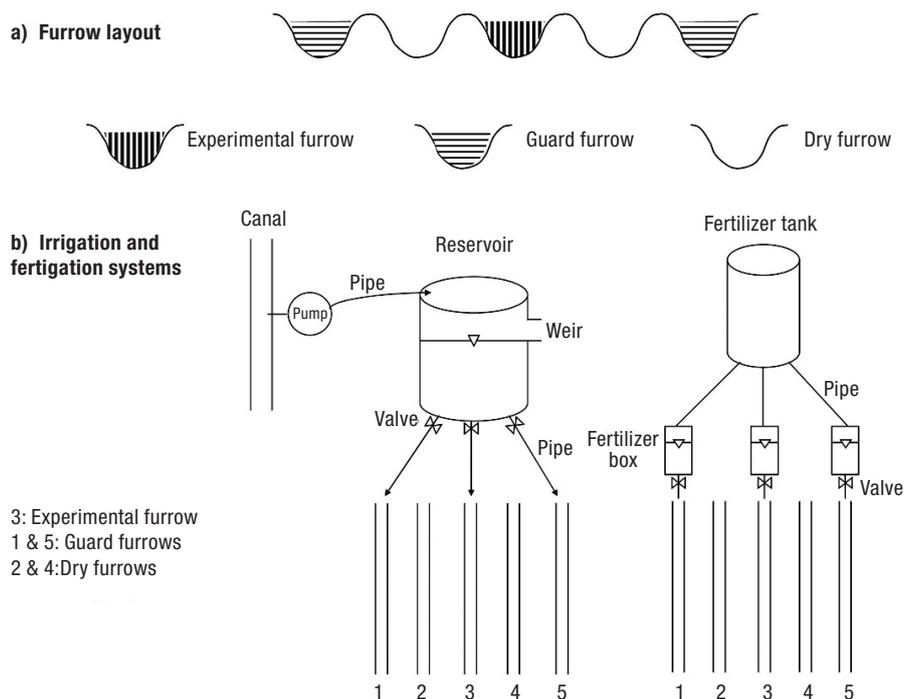


Figure 1. Furrow layout and three types of furrows (a); schematic of water distribution and fertilizer solution injection systems in alternate furrow fertigation (b).

The uniformity of fertilizer distribution in the crop root zone is a critical indicator for surface fertigation design and management. The distribution uniformity and the Christiansen's uniformity coefficient have been widely used for this purpose. Just as water deep percolation (DP_w) and runoff (RO_w) lead to estimate water application efficiency (E_w), fertilizer runoff (RO_f) and fertilizer leaching (L_f) lead to the estimation of the efficiency associated to fertilizer application (E_f):

$$E_w = 1 - (DP_w + RO_w) \quad [1]$$

$$E_f = 1 - (L_f + RO_f) \quad [2]$$

Fertilizer mass in runoff can be estimated by multiplying the average runoff water fertilizer concentration by the runoff volume. Water samples should be periodically collected at the furrow/border downstream end for fertilizer concentration determination. García-Navarro *et al.* (2000) proposed the use of electrical conductivity as a quick, inexpensive, indirect estimation of fertilizer concentration. In situ conductivity determinations can also be used to guide fertilizer application in commercial fertigation operations. The fertilizer runoff fraction (RO_f) is the percentage of the applied nitrate running off the field. Fertilizer leaching

can be calculated from experimental data using a solute balance equation or through properly calibrated simulation models.

Fertilizer application efficiency has only been used in a few works (Sabillón & Merkley, 2004; Ebrahimian & Playán, 2014), owing to the experimental difficulties in obtaining this indicator. Fertilizer runoff has often been used as a partial indicator of efficiency since runoff can be easily and accurately measured in field experiments. The estimation of fertilizer leaching requires intense experimental work before and after the fertigation event, and is affected by the strong spatial variability of soil water and fertilizer concentration, as well as by the sampling strategy. Field experiments on a sandy loam in Arizona (USA) showed that high potential for solute leaching under furrow-irrigated conditions with a very high degree of spatial variability (Silvertooth *et al.*, 1992). Conducting fertilization experiments, Jaynes *et al.* (1992) found that the average leaching depth of a mobile tracer applied with irrigation water was about 60% deeper than when the mobile tracer was pre-applied to the soil surface immediately before conventional irrigation in a level basin system. Monitoring nitrate movement in the soil solution using soil solution extractors, Janat (2007) indicated that furrow irrigation resulted in larger

leaching of nitrate below the rooting zone than drip fertigation. Fertilizer leaching can be estimated from the flow of deep percolation (obtained from a water balance equation) and from fertilizer concentration in the soil solution below the root zone (Mailhol *et al.*, 2001). Lysimeters of different sizes have also been used to measure nitrate leaching (Crevoisier *et al.*, 2008). Such measurements face the problem of representing the complete basin/border/furrow, thus requiring a statistical design and a sampling strategy which may be very demanding in terms of equipment and experimental effort. Standardized procedures for the experimental estimation of fertilizer leaching in the different surface irrigation methods are required to ease comparisons between research results and to firmly identify best fertigation practices.

Most fertigation studies have been carried on uncropped, bare soil, and have been restricted to just one fertigation event. However, plant fertilizer uptake plays a key role in the soil fertilizer cycle. This issue can only be analysed in fertigation experiments extending to the whole crop cycle (Janat, 2008; Zhang *et al.*, 2011) or even to a whole hydrological year. In such experiments, fertilizer use efficiency (ratio of crop yield to total applied fertilizer) is an important indicator.

Nitrogen fertilizers have commonly been used in surface fertigation studies. Playán & Faci (1997) used potassium bromide (a tracer known to mimic the transport dynamics of nitrate) to simulate nitrate dynamics in surface fertigation experiments. Since natural bromide levels are negligible in most soils, using this tracer makes pre-fertigation sampling unnecessary and facilitates the estimation of leaching. Additional authors have used bromide in different experimental fertigation conditions: furrows (Abbasi *et al.*, 2003c; Sabillón & Merkle, 2004) and borders/basins (Adamsen *et al.*, 2005; Zerihun *et al.*, 2005b). When plant uptake, yield and fertilizer use efficiency are to be investigated, nitrogen is the common experimental choice. To identify practices maximizing fertilizer distribution uniformity and/or minimizing fertilizer losses to runoff, most experimental research works applied the fertilizer (or the tracer) at different times during the irrigation event and with different durations. The interaction of fertilizer application with variables such as the type of surface irrigation system, infiltration and its spatial variability, or field slope or soil roughness, makes it difficult to extract general conclusions from these research works.

The cost and logistic problems of field experiments, the limitations that those problems impose on our ability to apply statistical analyses, and the difficulty of comparing results constitute a critical challenge. Surface fertigation numerical models have often been perceived as a solution to overcome these limitations.

Surface fertigation modelling

Modelling overland water flow and fertilizer transport is a key tool to analyse and optimize surface fertigation design and management. Field experimentation cannot be considered as an alternative approach, due to its inherent time and cost limitations. However, both approaches can be considered complementary. Simulation models have proven useful to identify fertigation guidelines. Once the predictive capacity of fertigation models is established, computer optimization can be applied to real problems with the aims of minimizing fertilizer losses or maximizing fertilizer application efficiency and uniformity. Simulation and optimization tools can also be applied to the development of sensitivity analyses for management and operational variables (*e.g.*, inflow discharge or fertilizer injection timing).

Understanding the equations governing overland and subsurface water flow and fertilizer transport and their computational methods, key assumptions and limitations is essential for successful model application. The numerical solution of these governing equations (for which closed solutions are not generally available) requires definition and proper treatment of boundary and initial conditions. Overland and subsurface, water and solute transfer equations can be solved in coupled fashion (all equations are solved in each time step) or in sequential fashion (overland flow is first solved, and then subsurface flow, with different arrangements for water and solute transport). The equations are described in the following sections.

Surface water flow

The hydrodynamic equations used in mathematical models to describe overland flow in surface irrigation are the equations of conservation of mass and momentum, known as the Saint-Venant equations (Chow, 1959; Strelkoff, 1969). These can be formulated as a set of hyperbolic equations:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} + \frac{\partial Z}{\partial \tau} = 0 \quad [3]$$

$$\frac{1}{Ag} \frac{\partial Q}{\partial t} + \frac{2Q}{A^2 g} \frac{\partial Q}{\partial x} + \left(1 - \frac{Q^2 T}{A^3 g}\right) \frac{\partial y}{\partial x} - S_0 + S_f = 0 \quad [4]$$

where A is the cross-sectional area [L^2]; t is the time from beginning of irrigation [T]; τ is intake opportunity time [T]; Q is discharge [$L^3 T^{-1}$]; x is the distance along field length [L]; Z is the infiltration rate [LT^{-1}]; g is the acceleration due to gravity [$L^3 T^{-1}$]; y is the depth of flow [L]; S_0 is the longitudinal slope of field [LL^{-1}]; S_f is the slope of energy grade line [LL^{-1}]; and T is the top width of flow [L].

Numerical models differ in the solution techniques and the underlying assumptions. The momentum equation is often simplified or in cases completely ignored to reduce computational complexity. Depending upon which simplifying assumptions are used, models can be grouped in decreasing order of complexity into four subclasses: hydrodynamic, zero-inertia, kinematic-wave, and volume balance.

Hydrodynamic models

The most complex and accurate approach is the full hydrodynamic numerical simulation model, which solves the complete form of the Saint-Venant equations. Such models can provide accurate simulations for a wide range of field conditions. Due to its accuracy, the hydrodynamic approach is often used to evaluate simpler models.

Zero-inertia models

These models are based on neglecting the acceleration and inertia terms (Strelkoff & Katopodes, 1977). Consequently, Eq. [4] becomes

$$\frac{\partial y}{\partial x} = S_0 - S_f \quad [5]$$

Equations [3] and [5] are parabolic, rather than hyperbolic, and the numerical solutions suited for these models are less complex than those required for hydrodynamic models. Consequently, zero-inertia models require less computation resources and time that is very important for the optimization process of surface fertigation.

Kinematic-wave models

The flow depth gradient $\left(\frac{\partial y}{\partial x}\right)$ and the inertial terms of the momentum equation (Eq. [4]) are often small in comparison with the bottom and friction slopes. Therefore, Eq. [4] can be further simplified to:

$$S_0 = S_f \quad [6]$$

This assumption implies that flow depth at a given point is uniform. The mathematical solution of the momentum equation is greatly simplified, but kinematic-wave models can only be applied to free-draining sloping fields. Kinematic-wave models are simpler to program and take far less computer time than hydrodynamic and zero-inertia models (Walker & Skogerboe, 1987).

Volume-balance models

The volume balance approach is primarily applied to the advance phase. Such models can be written for border, basin, or furrow conditions. The momentum equation is completely neglected, and substituted by hypotheses on flow depth. These models are based on the principle of mass conservation and on the assumption of normal flow depth at the upstream end (Walker & Skogerboe, 1987). The advance phase can be predicted using the volume balance approach in borders and furrows using the following equation:

$$Q_0 t_x = \int_0^x A(x,t) dx + \int_0^x Z(x,t) dx \quad [7]$$

where Q_0 is the flow rate at the inlet boundary; t_x is the time of advance to point x ; $A(x,t)$ is the cross-sectional area of surface flow, variable with distance (x) and time (t), $Z(x,t)$ is the cross-sectional area of infiltrated water, also variable with distance and time.

Two-dimensional hydrodynamic models

The one-dimensional zero-inertia and full hydrodynamic models have been frequently used to model surface fertigation. In the last two decades, two-dimensional hydrodynamic models have been used for basin simulation (Playán *et al.*, 1994a,b). In these two-dimensional models the simulation domain is drawn in a horizontal plane. Recently, Xu *et al.* (2013) used the two-dimensional form of the mass and momentum

conservation equations to simulate basin fertigation. Following Bradford & Sanders (2002), the governing equations can be written as:

$$\frac{\partial d}{\partial t} + \frac{\partial(du)}{\partial x} + \frac{\partial(dv)}{\partial y} = -i_c \quad [8]$$

$$\frac{\partial q}{\partial t} + \frac{\partial(qu)}{\partial x} + \frac{\partial(qv)}{\partial y} = gd \frac{\partial h}{\partial x} - \frac{n^2 u \sqrt{u^2 + v^2}}{d^{4/3}} \quad [9]$$

$$\frac{\partial p}{\partial t} + \frac{\partial(qu)}{\partial x} + \frac{\partial(pv)}{\partial y} = gd \frac{\partial h}{\partial x} - \frac{n^2 v \sqrt{u^2 + v^2}}{d^{4/3}} \quad [10]$$

where x and y are the spatial coordinates [L]; t is the temporal coordinate [T]; d is the surface water flow depth [L]; u and v are the depth-averaged velocity of surface water flow along the x and y directions [LT^{-1}], respectively; i_c is the infiltration rate [LT^{-1}], q and p are the unit discharges along the x and y directions, respectively [$\text{L}^3 \text{T}^{-1} \text{L}^{-1}$]; h is the water level [L] and n is the manning roughness [TL^{-3}].

Subsurface water flow

Two approaches have been used in fertigation models to determine soil infiltration: empirical infiltration equations and Richards analytical equation. In the first method, the infiltration equation is used to estimate water and solute application and to determine fertigation performance indicators. Empirical infiltration equations such as Kostiakov, Kostiakov-Lewis and branch Kostiakov have been extensively used in the literature (Walker & Skogerboe, 1987). The appropriate selection of an infiltration equation and the accurate estimation of infiltration parameters are key to the quality of simulation results. These simple empirical equations provide a simple approach to infiltration, but cannot provide insight about solute distribution in the soil or about solute leaching.

In the second method, the use of Richards equation permits to estimate soil water and solute distribution. In fertigation applications, this equation has been written in one- and two-dimensional forms. The one-dimensional form only considers the vertical spatial dimension, while the two-dimensional form considers a vertical and a horizontal spatial dimension. The two-dimensional form of Richards equation can be expressed as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i} \left[K(K_{ij}^\Lambda \frac{\partial h}{\partial x_j} + K_{iz}^\Lambda) \right] - S \quad [11]$$

where θ is the volumetric water content (dimensionless), h is the pressure head [L], S is a sink term [T^{-1}], x_i and x_j are the spatial coordinates [L], K_{ij}^Λ are components of a dimensionless anisotropy tensor K^Λ , and K is the unsaturated hydraulic conductivity function [L T^{-1}].

Surface solute transport

The three primary modes of solute transport in open channel flow are advection or convection (transport associated with the water flow), diffusion (transport associated with the concentration gradient, with solute flowing from regions of higher concentration to regions of lower concentration), and dispersion (transport associated with non-uniform velocity profiles). Diffusion is usually neglected in surface fertigation modelling. The advection-dispersion equation has been frequently applied to fertigation simulation. The one-dimensional cross-sectional average dispersion equation was presented by Cunge *et al.* (1980):

$$\frac{\partial(AC)}{\partial t} + \frac{\partial(AUC)}{\partial x} = \frac{\partial}{\partial x} \left(AK_x \frac{\partial C}{\partial x} \right) \quad [12]$$

where C and U are cross-sectional average concentration [ML^{-3}] and velocity [LT^{-1}], respectively; and K_x is the longitudinal dispersion coefficient [$\text{L}^2 \text{T}^{-1}$]. Coefficient K_x incorporates both dispersion due to differential advection and turbulent diffusion (Cunge *et al.*, 1980). The dispersion coefficient for transport in overland flow can be described as:

$$K_x = D_x U_x + D_d \quad [13]$$

where D_x is longitudinal dispersivity [L]; D_d is molecular diffusion in free water [$\text{L}^2 \text{T}^{-1}$], and U_x is overland flow velocity at location x [LT^{-1}].

Strelkoff *et al.* (2006) additionally neglected dispersion, and considered only advection effects. The advection equation can be written as:

$$\frac{\partial(C)}{\partial t} + U \frac{\partial(C)}{\partial x} = 0 \quad [14]$$

A two-dimensional form of the advection-dispersion equation has been recently proposed by Xu *et al.* (2013) for basin fertigation:

$$\frac{\partial(dC)}{\partial t} + \frac{\partial(qC)}{\partial x} + \frac{\partial(pC)}{\partial y} = \frac{\partial}{\partial x} \left(dD_x \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(dD_y \frac{\partial C}{\partial y} \right) - i_c \quad [15]$$

where C is the depth-averaged solute concentration [ML^{-3}]; d is the surface water flow depth [L]; D_x and

D_y are the solute dispersion along the x and y directions, respectively [L^2T^{-1}], i_c is the infiltration rate [LT^{-1}], and the other terms are as previously defined.

Subsurface solute transport

The subsurface solute transport equation is much more complicated than the surface solute transport equation, due to the consideration of zero- and first-order reaction and plant uptake, as well as the advection, dispersion and diffusion processes. For instance, Ebrahimian *et al.* (2013a) assumed that nitrate transfer in the soil can be represented by the following one-dimensional equation applied to a vertical line in the soil:

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial x_i} \left(\theta D_{ij} \frac{\partial c}{\partial x_j} \right) - \frac{\partial q_i c}{\partial x_i} + \gamma_w \theta - S c_s \quad [16]$$

where c is the nitrate concentration in the soil [ML^{-3}], q_i is the i -th component of the volumetric flux [LT^{-1}], D_{ij} is the dispersion coefficient tensor [L^2T^{-1}], γ_w is the zero-order rate constant for nitrate production by ammonium degradation in the soil solution [$ML^{-3}T^{-1}$], S is the sink term of the water flow in the Richards' equation, and c_s is the concentration of the sink term [ML^{-3}]. D_{ij} can be defined as follows (Simunek *et al.*, 1999):

$$\theta D_{ij}^w = D_T |q| \delta_{ij} + (D_L - D_T) \frac{q_j q_i}{|q|} + \theta D_w \tau_w \delta_{ij} \quad [17]$$

where D_w is the molecular diffusion coefficient in free water [$L^2 T^{-1}$]; τ_w is the tortuosity factor (dimensionless); δ_{ij} is the Kronecker delta function ($\delta_{ij} = 1$ if $i = j$, and $\delta_{ij} = 0$ if $i \neq j$); D_L is the longitudinal dispersivity [L]; and D_T is the transverse dispersivity [L].

Two strategies have been proposed for modelling solute transport in the soil. The first strategy uses the soil advection-dispersion equation. One- and two-dimensional forms of this equation have been used for border/basin and furrow irrigation, respectively (Zerihun *et al.*, 2005a; Ebrahimian *et al.*, 2013a). The two-dimensional approach is used to represent the soil underneath a cross-sectional furrow section. It counts on a vertical dimension (soil depth) and a horizontal dimension (furrow width).

The second strategy is a simplified approach adapted to the use of an empirical infiltration equation. The solute infiltrated in a point along the length of the field during a time interval can be estimated from the infil-

tration equation and the following equation (Playán & Faci, 1997; Abbasi *et al.*, 2003c):

$$F_z = (Z^{t+\Delta t} - Z^t) \times \frac{(C^{t+\Delta t} + C^t)}{2} \quad [18]$$

where F_z is the mass of solute infiltrated through the soil surface into the soil between two consecutive time steps (Δt) [M]; Z is the volume of infiltrated water per unit length [L^3] and C is the surface cross-sectional average concentration [ML^{-3}]. This approach does not permit to estimate nitrate leaching or nitrate application efficiency.

Developed surface fertigation models

A wide array of numerical techniques has been applied to solve the equations governing surface fertigation. Among them, the Karpic-Crockett method, the Crank-Nicholson finite difference scheme, the split-operator approach, the second-order total variation diminishing scheme, or the method of characteristics with cubic-spline interpolation and a time-weighted finite-difference scheme (García-Navarro *et al.*, 2000; Abbasi *et al.*, 2003c; Sabillón & Merkle, 2004; Zerihun *et al.*, 2005a; Burguete *et al.*, 2009a; Perea *et al.*, 2010b). The accuracy and stability of the numerical model depend on the selected numerical scheme and on its implementation. When solving the advection-dispersion equation, appropriate space and time discretization needs to be applied in order to avoid oscillatory behavior and artificial numerical dispersion. Thresholds are often applied to the Courant and Péclet numbers (Abbasi *et al.*, 2003c; Zerihun *et al.*, 2005a). This is particularly important to protect accuracy in the vicinity of sharp concentration fronts (Perea *et al.*, 2010b). Representative examples of the application of the above mentioned numerical techniques are presented in Table 1.

The first surface fertigation model was probably the SIFUM model developed by Boldt (1991) for surge furrow irrigation. This model used the output of the SIRMOD surface irrigation model (Walker, 2001) as input for solving the solute advection equation in an uncoupled fashion. In SIFUM, the Kostikov infiltration parameters were determined following the Blair & Smerdon (1987) method, and then used to estimate the mass of infiltrated solute. Boldt *et al.* (1994) presented SIFUM simulation results. A number of simulation scenarios including soil infiltration and injection management were considered in their study.

Table 1. Surface fertigation models developed for the simulation of surface and subsurface water flow and solute transport

Reference	Surface water flow*	Surface solute transport	Subsurface water flow	Subsurface solute transport
Boldt <i>et al.</i> (1994)	Hydrodynamic (1D)	Convection	Kostiakov	—
Playán & Faci (1996)	Hydrodynamic (1D)	Convection	Kostiakov-Lewis	—
García- Navarro <i>et al.</i> (2000)	Hydrodynamic (1D)	Convection-Dispersion	Kostiakov-Lewis	—
Abbasi <i>et al.</i> (2003c)	Zero-Inertia (1D)	Convection-Dispersion	Branch Kostiakov-Lewis	—
Sabillón & Merkle (2004)	Hydrodynamic (1D)	Convection-Dispersion	Kostiakov-Lewis	—
Adamsen <i>et al.</i> (2005)	Zero-Inertia (1D)	Convection	Kostiakov-Lewis	—
Zerihun <i>et al.</i> (2005)	Zero-Inertia (1D)	Convection-Dispersion	Richards	Convection-Dispersion (HYDRUS-1D)
Strelkoff <i>et al.</i> (2006)	Zero-Inertia (1D)	Convection	Kostiakov-Lewis	—
Burguete <i>et al.</i> (2009)	Hydrodynamic (1D)	Convection-Dispersion	Kostiakov-Lewis	—
Perea-Estrada <i>et al.</i> (2010b)	Zero-Inertia (1D)	Convection-Dispersion	Branch Kostiakov-Lewis	—
Ebrahimian <i>et al.</i> (2013a)	Zero-Inertia (1D)	Convection-Dispersion	Richards	Convection-Dispersion (HYDRUS-2D)
Zhang <i>et al.</i> (2013)	Hydrodynamic (1D)	Convection-Dispersion	Kostiakov	—
Xu <i>et al.</i> (2013)	Hydrodynamic (2D)	Convection-Dispersion	Kostiakov	—

* 1D: one-dimensional; 2D: two-dimensional.

Playán & Faci (1997) and García-Navarro *et al.* (2000) developed one-dimensional border fertigation models simulating solute transport considering the advection and advection-dispersion approaches, respectively. García-Navarro *et al.* (2000) reported that as the duration of fertilizer injection increased, the effects of dispersion were substantially relevant. As a consequence, the loss of accuracy derived from the use of an advection equation could be irrelevant in some specific cases. García-Navarro *et al.* (2000) introduced a significant improvement in the border fertigation model by introducing the dispersion effect. However, the one-dimensional assumption of water and fertilizer transport can limit the model application to specific field geometries, particularly in the case of basin irrigation.

Abbasi *et al.* (2003c) developed a one-dimensional surface fertigation model for furrow irrigation. They used a zero-inertia furrow irrigation model and an advection-dispersion equation. The model was applied to blocked-end and free-draining furrows. Model performance was satisfactory since the one-dimensional hypothesis on water and surface transport is more adequate for furrows than for borders and basins.

model was successfully applied to the simulation of alternate furrow irrigation (Ebrahimian *et al.*, 2013a).

Sabillón & Merkle (2004) developed a one dimensional furrow fertigation model based on a hydrodynamic surface irrigation model and an advection-dispersion solute transport equation. They stated that dispersion had very little effect on solute transport. Two indicators (solute application efficiency and uniformity) were proposed to guide the identification of the best injection start time and duration for different soil infiltration characteristics.

Zerihun *et al.* (2005a) presented a one-dimensional coupled surface-subsurface solute transport model for border and basin irrigation. This model applied zero-inertia and advection-dispersion models for surface water and solute transport, and Richards and advection-dispersion equations (HYDRUS-1D; Simunek *et al.*, 1998) for subsurface transport. Field verification indicated that the model could successfully predict one-dimensional solute transport processes in irrigation basins and borders, provided that the model assumptions were met under field conditions (Zerihun *et al.*, 2005b).

Strelkoff *et al.* (2006) developed a surface fertigation model by linking an advection model to the SRFR surface irrigation simulation model (Strelkoff *et al.*, 1998). These authors assumed that non-reactive chemicals were transported by advection of the flowing water. Consequently, no mixing, dispersion, or chemical diffusion were considered. The results of this simplified model were in agreement with those of a complete advection-diffusion model in terms of infiltrated fertilizer distribution (Perea-Estrada, 2005).

Burguete *et al.* (2007) compared coupled and uncoupled numerical methods for solving the surface water flow and solute transport equations, and reported that the coupled solution showed the best performance. Burguete *et al.* (2009a) developed a one-dimensional furrow fertigation model using a coupled solution. The infiltration parameters and the roughness coefficient were estimated using error minimization techniques. Model simulations proved useful to predict concentration distribution in time and space for different fertilizer application possibilities in furrows and particularly in level furrow systems (Burguete *et al.*, 2009b). The level-furrow system was simulated as a network of interconnected furrows.

Perea *et al.* (2010a,b) developed and validated an advection-dispersion model to simulate fertilizer transport in furrow irrigation. The evolution in time and space of solute concentration pulses was adequately predicted. These authors highlighted the importance of accurate inflow measurements for estimating infiltration parameters and consequently for overall modeling accuracy.

Zhang *et al.* (2013) developed a one-dimensional numerical model for basin fertigation. They coupled a complete hydrodynamic model based on the Saint-Venant equations with an advection-dispersion equation with depth-averaged solute concentration in order to simulate surface water flow and solute transport. The model exhibited adequate performance when reproducing fertilizer application experiments characterized by different application timings. Due to the transversal variations of water velocity and depth characterizing border and particularly basin irrigation, a two-dimensional fertigation model was used to improve modelling accuracy. For this reason, Xu *et al.* (2013) proposed a two-dimensional coupled model for simulating surface water and solute transfer in basin fertigation.

Ebrahimian *et al.* (2013b) presented a 1D surface and 2D subsurface simulation-optimization model

to minimize nitrate losses in two types of alternate furrow fertigation (variable and fixed alternate furrow irrigation) and in conventional furrow irrigation. The model used numerical surface fertigation (Abbasi *et al.*, 2003c) and soil water (SWMS-2D) models to simulate water flow and nitrate transport in the soil surface and subsurface, respectively. A genetic algorithm was used to solve the optimization problem. Four decision variables (inflow discharge, cutoff time, start time and duration of fertilizer solution injection) were optimized to minimize the selected objective function (nitrate loss) during a maize growing season. The simulation-optimization model succeeded in substantially reducing nitrate loss, as compared to the field conditions for all irrigation treatments. In a succeeding work, Ebrahimian & Playán (2014) applied this simulation-optimization fertigation model to maximize two objective functions based on water and fertilizer application efficiency and uniformity. This approach substantially improved water and nitrate application efficiency and uniformity, compared to experimental conditions. Improvements were more important in conventional furrow fertigation than in alternate furrow fertigation.

The review of the developed models permits to single out the following approaches as most adequate for future developments: 1) complete hydrodynamic or zero-inertia model to simulate surface water flow; 2) the advection-dispersion equation to simulate surface and subsurface solute transport; 3) the Richards equation to simulate subsurface water flow; and 4) optimization algorithms to identify optimum fertigation recommendations. The performance of models above was found to strongly depend on the field calibration efforts. This point is particularly important for subsurface water and solute transport, where uncertainties in the calibration process seem relevant, owing to experimental difficulties.

Fertigation recommendations: key management variables

In the absence of appropriate management, surface fertigation performance can be low when compared to conventional fertilizer application methods (Gardner & Roth, 1984; Jaynes *et al.*, 1988). For instance, if an irrigation event shows high percolation losses, fertilizer injection early in the irrigation time will lead to relevant fertilizer leaching (Jaynes *et al.*, 1992). Conver-

sely, if the irrigation event shows large runoff losses, injecting fertilizer late in the irrigation time will lead to large runoff losses (Ebrahimian *et al.*, 2013b). Key questions in recommending fertigation practices include when, how much and what kind of fertilizer to apply in surface irrigation water. Answers depend on the characteristics of the irrigation system, the crop (aspects such as daily nutrient requirements or soil root distribution), the fertilizer (*e.g.*, solubility), and the quality of irrigation water and soil. In addition, a question specific to surface fertigation is how to manage fertilizer application in the irrigation stream.

A number of surface fertigation papers aiming at answering the last question resorted to sentences in the line of “there are still no adequate guidelines for the proper design and management of surface fertigation” (Abbasi *et al.*, 2003c; Adamsen *et al.*, 2005; Moravejalahkami *et al.*, 2012). Fertigation guidelines in pressurized irrigation systems are relatively simple and available (Adamsen *et al.*, 2005). However, the practice of surface fertigation is much more complex because of water distributing over the field surface and because of the spatial and temporal variability of soil characteristics. After decades of research, great efforts have been devoted to develop appropriate management guidelines. However, apparent inconsistencies and contradictions can often be identified in fertigation recommendations. These are grounded in issues such as the specific irrigation method, fertilizer management, or the simplifications adopted in numerical models. Hence, in order to address a specific surface fertigation management problem, relevant literature should be compared and screened for similitudes within each study case.

Standardization of performance indicators is required to render management alternatives comparable. Zerihun *et al.* (2003) introduced a valuable set of indicators for nitrogen fertigation management. This set can be readily applied to other fertilizers and to different irrigation systems. The fertilizer Distribution Uniformity of the low quarter (or half) and the fertilizer Application Efficiency have been used in most literature references (Boldt *et al.*, 1994; Playán & Faci, 1997; García-Navarro *et al.*, 2000; Abbasi *et al.*, 2003b; Zerihun *et al.*, 2003; Sabillón & Merkley, 2004; Adamsen *et al.*, 2005; Perea-Estrada, 2005; Strelkoff *et al.*, 2006; Ebrahimian *et al.*, 2013b; Ebrahimian & Playán, 2014). All these references analyzed fertilizer distribution uniformity. However, only Sabillón & Merkley (2004), Ebrahimian *et al.* (2013b) and

Ebrahimian & Playán (2014) addressed fertilizer application efficiency. Almost all authors above showed concern about surface fertigation performance, taking into consideration the allegedly low uniformity and efficiency characterizing surface irrigation systems. These authors also highlighted the potential of surface fertigation to improve fertilizer application efficiency and uniformity in irrigated areas.

Fertigation performance indicators are affected by a number of management variables. Among them, water inflow discharge and its hydrograph during the injection (Abbasi *et al.*, 2003c; Moravejalahkami *et al.*, 2012), soil infiltration (Abbasi *et al.*, 2003c; Sabillón & Merkley, 2004), start time and duration of fertilizer application, irrigation depth (Abbasi *et al.*, 2003c; Ebrahimian *et al.*, 2012b), the method of fertilizer injection (pulsed or continuous) (Boldt *et al.*, 1994; Playán & Faci, 1997; García-Navarro *et al.*, 2000; Perea-Estrada, 2005), tillage record before fertigation (Bandaranayake *et al.*, 1998), concentration of fertilizer solution (Abbasi *et al.*, 2003c), the dispersion coefficient (García-Navarro *et al.*, 2000; Abbasi *et al.*, 2003c), the surface irrigation method (Ebrahimian *et al.*, 2013b), or the field slope and the downstream condition (free draining or blocked end). These variables differ in their effect on management indicators. Abbasi *et al.* (2003c) performed a sensitivity analysis on a surface fertigation simulation model, and reported that inflow discharge, soil infiltration and start time for fertilizer injection showed the largest effects on fertilizer distribution uniformity. The concentration of fertilizer solution and the dispersion coefficient showed the lowest effects. Among the most effective factors, the start time and duration of fertilizer injection are easy to control at farm level, and therefore stand as key management variables. Ebrahimian *et al.* (2013b) reported on 50% reduction of nitrate losses (respect to the experimental conditions) only by optimizing the start time and the duration of fertilizer injection. Sabillón & Merkley (2004) reported that soil infiltration characteristics and furrow length and slope had high impact on the adequate fertilizer injection timing. Playán & Faci (1997) showed that short fertilizer application times led to low fertilizer uniformity distribution. This finding was complemented by Perea-Estrada (2005), who indicated that (despite its low uniformity) surface fertigation by short pulses could help reduce leaching and runoff losses. More research is needed to evaluate the feasibility of short-pulse surface fertigation.

Fertilizer injection timing: start time and duration

As previously stated, researchers have paid more attention to fertilizer injection timing than to other fertigation management variables. Recommendations have been issued based on field experiments and simulation results. Contradictions are abundant in the recommendations. For instance, solute application during the entire irrigation event, or during the second half of the irrigation (Abbasi *et al.*, 2003c) and fertilizer injection during the first half of the irrigation event (Ebrahimian *et al.*, 2013b) have been recommended. Similarly, García-Navarro *et al.* (2000) recommended short time injections, while Abbasi *et al.* (2003c) recommended the long injections. These apparent discrepancies can be attributed to differences in irrigation methods and parameters, fertilizers and soil properties (particularly infiltration) as well as to the targeted fertigation performance indicators. For instance, the fertigation management recommendations by Abbasi *et al.* (2003c) and Ebrahimian *et al.* (2013b) are based on fertigation application unifor-

mity and efficiency, respectively. All the results reported in these experiments deserve scientific credit. However, the complexity of the problem seems to prevent the extraction of general conclusions.

Tables 2 to 4 describe selected surface fertigation references classified by the specific irrigation system: free-draining furrows (Table 2), blocked-end furrows including surge fertigation (Table 3), and border/basin irrigation (Table 4). References are chronologically listed within each table to facilitate the assessment of progress in surface fertigation studies. The experimental procedure is a major classification criterion for surface fertigation studies, with two options: field experimentation and modelling (simulation or simulation-optimization). In the absence of a generic analysis of surface fertigation, all listed references recommended fertigation management practices for specific conditions. References often differ in the targeted irrigation performance indicator. While some researchers focused on fertilizer distribution uniformity, others attempted to limit fertilizer runoff losses or leaching below the root zone.

Most surface fertigation studies were performed on free-draining furrows (Table 2). The assimilation of

Table 2. Summary and remarks of the selected studies about free draining furrow fertigation

Reference	Remarks and recommendations	Soil/Plant	Fertilizer/ Solute	Indicator	Achieved by
Sabillón & Merkley (2004)	Injection start time between 5 and 95% of advance time. Injection duration between 5 and 15% of irrigation cut off time.	Most soils/—	Potassium bromide	Fertilizer distribution efficiency and uniformity	Modeling
Perea-Estrada (2005)	Short time injection increases efficiency and decreases uniformity. Higher uniformity and efficiency in free draining and blocked end, respectively. Injection during the entire irrigation event was not good due to trade-off between runoff and deep percolation.	Loamy sand and clay loam/—	Potassium bromide	Fertilizer distribution uniformity for blocked end. Fertilizer distribution efficiency for free end	Field experiment
Burguete <i>et al.</i> (2009a,b)	Injection during the entire irrigation time.	Alluvial coarse loam/—	Commercial fertilizer 12:9:34	Fertilizer distribution uniformity	Modeling
Navabian <i>et al.</i> (2010)	Fertilizer injection during cutback phase. Cultivation and non-cultivation conditions affect on the optimum injection time.	Clay loam/ Maize	Potassium nitrate	Fertilizer losses	Modeling (Optimization)
Abbasi <i>et al.</i> (2011)	Injection at 20 minutes before irrigation cutoff time.	Loam/ Maize	Urea	Fertilizer distribution uniformity	Field experiment
Ebrahimian <i>et al.</i> (2013b)	Injection in the first half of irrigation time. Decrease inflow discharge and increase irrigation cutoff time.	Clay loam/ Maize	Ammonium nitrate	Fertilizer losses	Modeling (Optimization)

Table 3. Summary and remarks of the selected studies about blocked-end furrow and surge fertigation

Reference	Remarks and recommendations	Soil/Plant	Fertilizer/ Solute	Indicator	Achieved by
<i>Blocked end furrow irrigation</i>					
Abbasi <i>et al.</i> (2003b)	Injection at the short time under high irrigation depth	Sandy loam/—	Calcium bromide	Fertilizer distribution uniformity	Field experiment
Abbasi <i>et al.</i> (2003c)	Injection during the entire of the second half of irrigation time	Sandy loam/—	Calcium bromide	Fertilizer distribution uniformity	Field experiment
<i>Surge irrigation</i>					
Watts <i>et al.</i> (1994)	Under blocked end condition: For high permeable soil: injection at the curback phase For moderate and low permeable soil: injection at the surges of advanced phase	Various soil SCS* families/—	Urea-Ammonium	Nitrate leaching	Modeling
Boldt <i>et al.</i> (1994)	For high permeable soil: injection at the all surges and irrigation phases For moderate and low permeable soil: injection at the surges of advance phase	Various soil SCS families/—	Nitrate-Nitrogen	Runoff loss and fertilizer distribution uniformity	Modeling

* SCS: Soil Conservation Service.

furrow flow to a one-dimensional problem provides conceptual simplicity and adds to the modelling accuracy. Three major groups of target fertigation performance indicators can be considered for furrows: 1) fertilizer distribution uniformity; 2) fertilizer application efficiency; and 3) fertilizer distribution uniformity and

application efficiency. The following general recommendations can be extracted for the fertigation of free-draining furrows (Table 1):

— To achieve high fertilizer distribution uniformity, fertilizer injection should be pulsed, and take place towards the end of the irrigation event. In this case,

Table 4. Summary and remarks of the selected studies about border/basin fertigation

Reference	Remarks and recommendations	Soil/Plant	Fertilizer/ Solute	Indicator	Achieved by
Playán & Faci (1997)	Short application times do not represent an adequate choice. Short applications starting late in the irrigation event yield better uniformities than applications started early	Bare soil/Corn	Bromide & Ammonium nitrate	Fertilizer distribution uniformity	Modeling
García-Navarro <i>et al.</i> (2000)	Short fertilizer applications toward the beginning or the end of the irrigation event should be avoided	Impervious border/—	Ammonium nitrate	Fertilizer distribution	Modeling
Adamsen <i>et al.</i> (2005)	Under blocked end border with side furrows conditions: injection at the entire irrigation time or the first half of irrigation time	Fine sand/Date palms	Bromide	Fertilizer distribution uniformity	Field experiment
Zhang <i>et al.</i> (2013)	—	Silty loam/Wheat	Ammonium sulphate	—	Modeling
Xu <i>et al.</i> (2013)	—	Silty loam/Wheat	Ammonium sulphate	—	Modeling

the risk of fertilizer runoff losses is high. Injection during the entire irrigation time is also a good option in terms of uniformity, and can help control of fertilizer runoff losses.

— To achieve high fertilizer application efficiency, injection during the first half of irrigation is an adequate option.

— To maximize both uniformity and efficiency, fertilizer solution should start after the completion of advance and end before the time of cut off.

A few research works focused on the application of fertigation in blocked-end furrows. The limited number of references limits the possibilities for extracting recommendations. However, it seems important to continue research on blocked-end furrows and borders.

Two references were found for surge furrow fertigation (free-draining and blocked-end), both based on models. Simulations were performed covering a wide range of soil, inflow and fertigation management options. In free-draining configurations, injection in all surges was recommended for high-intake soils; injection during the advance phase surges was recommended for medium and low intake soils (Boldt *et al.*, 1994). In blocked-end configurations, Watts *et al.* (1994) recommended injection at the cutback phase for high permeable soil and at the surges of advance for moderate and low permeable soils.

A limited number of references containing recommendations for basin and border fertigation have been found. Field experimentation and numerical approaches have been applied to basin and border fertigation, and recommendations for fertigation management have been issued:

— In basins and borders, very short (pulsed) fertilizer applications often result in fertilizer uniformity lower than irrigation uniformity. If needed, very short applications can be made between one-third and one-half of the advance time. Such applications may correspond to the sudden addition of a mass of solid fertilizer.

— In free-draining borders, short applications applied late in the irrigation event may be very uniform, but can lead to major fertilizer runoff losses. Fertilizer application late in the irrigation event should be avoided in all cases.

— The use of long fertilizer applications is a conservative practice in borders and basins. Applications should start early in the irrigation event and end near the end of the irrigation event. Basin and border irrigation uniformity is often high. As a consequence, the

application of fertilizer during the complete irrigation event often constitutes an interesting alternative.

— If large percolation losses are expected, it is important to avoid fertigation at the onset of irrigation. This will control fertilizer percolation losses at the upstream end of the field. Soil characteristics, root depth and fertilizer uptake by plants should be considered when judging these systems.

Other effective factors

In addition to the fertigation timing parameters, other factors have been reported to affect fertigation performance:

Fertigation in alternate (every-other) furrows

Ebrahimian *et al.* (2012b) characterized the combined effect of alternate furrow irrigation and surface fertigation on water and nitrate losses. Two types of alternate furrow irrigation, *i.e.*, variable alternate furrow irrigation (AFI) and fixed alternate furrow irrigation (FFI), as well as conventional furrow irrigation (CFI) were considered in the experiments. Increased lateral water movement under alternate irrigation resulted in lower water and nitrate losses via runoff and deep percolation. Even though the amount of applied water and fertilizer per unit area was doubled in the CFI treatment relative to alternate furrow treatments, soil water and nitrate concentrations in AFI and FFI were much higher than half of the corresponding values in the CFI treatment. These results indicated that alternate furrow irrigation has potential to keep more water and nitrate in the root zone due to its increased potential for horizontal movement of water and nitrate.

Furrow flow depth

Abbasi *et al.* (2003a) reported on the impact of furrow flow depth on infiltrated water and bromide. Field experiments used short blocked-end furrows, and combined different flow depths and durations. Irrigation with high flow depth and short application time improved the distribution of water and solutes within the soil profile, while decreasing deep percolation of water and solutes as compared to low and moderate water levels and relatively long duration times.

Inflow hydrograph

The inflow rate and the shape of the inflow hydrograph can substantially affect surface water flow and solute transport. Moravejalahkami *et al.* (2012) presented modified furrow inflow hydrograph designs and evaluated them in field conditions. Zero-inertia simulations were also presented. These authors considered the following alternatives: constant inflow hydrograph, modified cutback inflow hydrograph, nonlinear reducing inflow hydrograph and modified increased discharge inflow hydrograph shape. Modified inflow hydrograph shapes significantly reduced runoff. Modified increased discharge inflow hydrograph shape resulted in higher solute uniformity. Fertilizer runoff losses changed with the different inflow hydrograph shapes, reaching a minimum value with the modified increased discharge inflow hydrograph shape. Further research is needed on the impact of inflow hydrographs on furrow fertigation efficiency, uniformity and runoff. The practical application of the proposed techniques needs to be assessed.

Fertigation in meandering furrows

Furrow irrigation is often performed in steep slopes, when the soil depth or the required investment prevents adequate levelling. In these cases, standard furrows with steep slopes may result in contamination of surface waters due to water and fertilizer runoff. Meandering furrows can address this problem by showing lower average slope and increasing furrow length. As a consequence, furrow infiltration will increase and pollution could be effectively controlled. Soroush *et al.* (2012) examined the effects of meandering furrow irrigation and field slope on the hydraulic parameters, water and fertilizer application uniformity and efficiency. Experimental results indicated that meandering furrows can improve application efficiency and decelerate advance, as compared to standard furrows.

Water and soil quality

Kafkafi & Tarchitzky (2011) highlighted the effect of irrigation water quality on plant nutrition and on fertilizer-water interaction. The chemical quality of water and soil may affect soil nutrient distribution and crop fertilizer uptake (Matijević *et al.*, 2012). The im-

portant aspect of water chemical quality and soil quality (*e.g.*, salinity and alkalinity) on surface fertigation performance has not been addressed in the literature. However, fertilizer solubility in saline and alkaline water and soil ion exchangeable capacity may affect fertigation design parameters. Research is needed on these issues, particularly in arid and semi-arid regions.

Nutrient uptake depth vs. root depth

The estimation of effective rooting depth is necessary for the efficient management of surface fertigation systems (Zerihun *et al.*, 2003). The upper part of plant roots has often been shown to uptake most of the applied nutrients (Burns, 1980; Thorup-Kristensen, 2006). This upper part is known as the nutrient uptake depth. When fertilizers are stored below the effective root depth, plant roots cannot uptake them. Considering nutrient uptake depth by plants roots instead of total root depth will result in different estimates of fertilizer leaching and application efficiency. Further research is needed to assess the effective root depth for nutrient uptake and to apply this knowledge to fertigation management.

Research gaps and needs

Despite the fact that a number of research works have been conducted on surface fertigation modelling, agreement has not been reached about the relevance of dispersion effects on overland solute transport. While some works recommend ignoring dispersion (Abbasi *et al.*, 2003c; Sabillón & Merkley, 2004; Strelkoff *et al.*, 2006), other works recommend considering it (García-Navarro *et al.*, 2000; Perea *et al.*, 2010b). The relevance of the dispersion process seems linked to factors such as the type of fertilizer, the inflow discharge, the irrigation method, the basin/border/furrow length, or soil infiltration and roughness. Abbasi *et al.* (2003c) reported that longitudinal dispersivity did not play an important role in their experiments. This could be attributed to the short experimental furrows and to the small confined flow areas characterizing furrow irrigation. However, Perea *et al.* (2010a) indicated that the furrow surface roughness and the resulting low velocity increased dispersion. These authors also reported that ignoring dispersion in surface fertigation modelling led to an overestimation

of the infiltrated solute mass. Since the introduction of dispersion does not lead to relevant programming or practical problems, this seems to be a conservative option. However, further research is needed to elucidate the conditions in which dispersion is needed to obtain accurate estimations of fertigation performance. Regarding subsurface solute transport, the use of dispersion is not a matter of scientific discussion. Recently, Ebrahimian *et al.* (2013a) evidenced the relevance of longitudinal and transversal dispersion in nitrate transport within the soil underneath fertigated furrows.

Almost all developed surface fertigation models assume one-dimensional surface water flow and solute transport. This assumption is adequate for furrow irrigation, but limited for border and particularly for basin irrigation. To obtain high accurate simulation results, two-dimensional surface water flow and solute transport should be considered for border and basin fertigation in future research, particularly under poor levelling quality (solutes may concentrate on the low spots of the field). Additional research is also needed to examine the effects of the variation of soil solute concentration within a furrow soil cross section. This is particularly important to assess if fertilizer is stored in the root zone. Solute transport through soil bypass channels and dead zones can challenge simulation results, particularly when assuming one-dimensional soil flow (Zerihun *et al.*, 2005b). Complete two-dimensional simulation models (overland and soil) are needed to optimize fertilizer management and to obtain better recommendations for basin/border fertigation. Most soil water models use the one-dimensional approach (Zerihun *et al.*, 2005a; Navabian *et al.*, 2010). Ebrahimian *et al.* (2012a) used a two-dimensional soil water model, and reported on its comparative advantages. Two-dimensional soil modelling (one vertical dimension and one horizontal cross-sectional dimension) is particularly important for alternate furrow irrigation, where lateral infiltration is stronger than in conventional furrow irrigation. The complexity of such modelling approach has also been documented, along with the required computational effort. The coupling of two-dimensional surface and subsurface simulation models, with inclusion of surface microtopography and subsurface heterogeneity, is a key subject for future research.

While reviewing coupled surface-subsurface flow processes, Furman (2008) stated the need to include vertical momentum (due to infiltration) transfer and expand the use of fully coupled models. In addition,

surface modelling capabilities should be extended to fertilizer transport aspects such as reaction, volatilization, sorption/desorption, and dissolution/precipitation (Zerihun *et al.*, 2005b).

Optimization approaches support the design and management of surface fertigation systems optimizing water and fertilizer application uniformity and efficiency, as well as crop yield. Moreover, all surface fertigation models to date were developed to analyse a single fertigation event. The development of seasonal surface fertigation models is an additional research gap from the agricultural, environmental and economic points of view. Crop models should also be coupled to fertigation models to assess the effect of fertigation practices on water and nutrient uptake, crop yield, net economic margin and fertilizer leaching.

Field experiments and model developments are still required for surge fertigation. No experimental data of surge fertigation has yet been reported. As a consequence, the calibration and validation of surge fertigation models has not been performed. The capability of these models to obtain fertigation management recommendations for surge fertigation needs to be assessed.

The development of reference experimental data sets will be very important to facilitate progress in surface fertigation models. Modelling will continue to be a key tool on surface fertigation, since the complexity of the problem does not permit to extract firm conclusions on the best fertigation management rules for different irrigation systems, soils or irrigation conditions. As a consequence, the present combination of modelling and experimentation efforts should be applied to the validation of a new generation of models with improved capabilities. Such models will address farmers' challenges in relation to water and fertilizer conservation and to the sustainability of surface fertigation systems.

While the surface transport of solutes can be predicted reasonably well, the literature review indicated less certainty about the prediction of subsurface transport. As a result, field-measured distribution of solutes may differ substantially from current model predictions. Part of the problem lies in the soil spatial variability and in preferential flow. Additionally, standardization is needed in the protocols used for field estimation of fertilizer leaching. Commonly agreed approaches are required in issues like the timing of pre- and post-irrigation soil sampling, or the number of soil sampling points required characterizing ferti-

gation performance in a given field. Soil sampling is basically still a function of logistics and labour availability.

A final key problem is that fertigation performance is ultimately measured by how much fertilizer is recovered by the crop, and this depends on fertilizer transformations and transport induced by subsequent water applications. A combination of experimental and simulation approaches seem required to address this and other bottlenecks. The calibration of advanced models to specific conditions seems to be the key to obtain site-specific recommendations ready for farmers' adoption.

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