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Review

A Review of HYDRUS 2D/3D Applications for Simulations of Water Dynamics, Root Uptake and Solute Transport in Tree Crops under Drip Irrigation

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Abstract: Orchards with tree crops are of critical importance to the global economy and to the environment due to their ability to be productive for many years without the need for replanting. They are also better adapted to extreme climatic conditions compared to other crops. However, new challenges are emerging as climate change threatens both tree production and water supply. Drip irrigation (surface and subsurface) is an irrigation method that has the potential to save water and nutrients by placing water directly into the root zone and minimizing evaporation. Many irrigation designs and strategies have been tested to best perform drip irrigation for any given soil, crop and/or climate conditions. The researchers' need to find the optimal combination of irrigation management and design in the most economical and effortless way led to the use of comprehensive numerical models such as HYDRUS 2D/3D. HYDRUS 2D/3D is a widely used mathematical model for studying vadose zone flow and transport processes. A review of HYDRUS 2D/3D applications for simulations of water dynamics, root uptake and solute transport under drip irrigation in the four most common categories of tree crops (citrus, olive, avocado and deciduous fruit/nuts) is presented in this study. The review promotes a better understanding of the effect of different drip irrigation designs and treatments, as well as the reliability provided by HYDRUS 2D/3D in the evaluation of the above. This manuscript also indicates gaps and future challenges regarding the use of the model in simulations of drip irrigation in tree crops.

Keywords: HYDRUS 2D/3D; drip irrigation; trees; irrigation system; irrigation treatment; model efficiency

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1. Introduction

Worldwide, water resources are under pressure as population growth and agricultural intensification have resulted in an increased demand. Climate change combined with the resulting desertification, will exacerbate the problem and increase the areas characterized by severe drought [1]. According to the FAO [2], agriculture is the largest consumer of water, accounting for almost 70% of global freshwater withdrawals, while 10% is used for domestic consumption and the rest for industry. Due to water shortage and water–climate effects, in the last decades an alternative practice for irrigation has become the use of wastewater [3]. However, the use of wastewater is still being tested for potential negative effects on soil and plants after long-term applications [4]. Thus, the need for more efficient and optimized use of water in irrigation is still critical [5].

Micro-irrigation, such as micro-sprinkler irrigation, drip irrigation, microtubing, etc., is the preferred method of irrigation by farmers owing to its low cost and water efficiency, with drip irrigation being one of the most common practices for vegetable and perennial crops such as fruit trees. Drip irrigation provides the possibility of precise water and chemical application in terms of both quantity and location, and therefore maximal water and nutrient uptake, while minimizing leaching from the root zone [6]. In addition, drip irrigation can be adapted to a wide range of topographic features, soil conditions and crop types [7]. Drip irrigation systems consist of small emitters that are either buried (subsurface drip irrigation) or placed on the soil surface (surface drip irrigation) and deliver water at a controlled rate [8]. In this regard, drip irrigation provides a high level of management, and allows for the accurate application of irrigation according to crop water needs, especially under orchard conditions [9].

Quantifying soil moisture content and chemical nutrient concentrations under a micro-irrigation system is a challenging task due to variations in soil hydraulic properties, emitter discharge rates, irrigation volume and frequency and water uptake by roots. Due to these uncertainties, sub-root zone seepage and nutrient leaching may occur, even though the applied water is equal to or less than the crop demand [6,10]. In addition, field experiments and measurements to determine water movement and chemical concentration are very time-consuming and expensive [11]. Therefore, mathematical/conceptual models have been developed for estimating water and solute transport in the vadose zone [12–16]. The modeling approach, although considered to be a useful alternative to field measurements, constantly includes uncertainties. Thus, using the best-fit model can produce more reliable results for sustainable agriculture policymakers. The most complete, reliable and widely used software package for simulating water, heat and solute movement in two- and three-dimensional variably saturated porous media is HYDRUS 2D/3D [17]. An important advantage of HYDRUS 2D/3D compared to other similar models is that there are no limitations to a specific spatial or temporal scale [18]. The model has been used for many applications over the years and especially for agricultural applications. Compared to other unsaturated zone models, HYDRUS provides users with more options for evaluating different irrigation schedules [19–22], studies on root water uptake [23–27] and leaching of nutrients and contaminants [6,28–33]. It has also been used extensively to evaluate the effects of different irrigation and fertigation strategies/treatments [6,34–36].

Since Skaggs et al. [37] effectively compared HYDRUS-2D simulations of drip irrigation with experimental field observations, the model has proven to be highly suitable for studies of drip irrigation studies under many kinds of cultivation [21,38–45]. Although these studies indicate the importance of numerical modeling in designing irrigation and fertigation systems for different crops, most studies are conducted for annual crops. The literature on modeling studies of drip irrigation for perennial horticultural crops, such as fruit and nut trees, is extremely limited. Depending on the age of the tree, the crop development stage, the percentage of soil cover and the local conditions, the water requirements of trees can be considered as quite high. In addition, trees control factors such as soil moisture dynamics through canopy interception and shading [46], root water uptake and transpiration [23]. All these factors distinguish tree crops from annual crops by the way in which irrigation water and nutrients are applied. This fact makes further investigation imperative (given the existing gap) involving simulations of water and solvent movement in the root zone of a tree under drip irrigation using models such as the widely used HYDRUS (2D/3D) model.

This review is intended to provide an overview of the HYDRUS 2D/3D applications for simulating water dynamics, root uptake and solute transport in tree crops under drip irrigation. In the present work, tree crops are divided into the four most common categories: citrus trees, olive trees, avocado trees and deciduous fruit (pear, apple and jujube) and nut (almond, pistachio, etc.) trees. These crop categories differ in their water stress tolerance, cultivation and fertilization practices and yield/harvest time. The numerical model HYDRUS 2D/3D is presented in Section 2. The application of the model to drip-irrigated citrus trees, olive trees, avocado trees and deciduous fruit and nut trees is presented in Sections 3, 4, 5 and Section 6, respectively.

2. HYDRUS 2D/3D Software

The Windows-based HYDRUS 2D/3D model [18] (Figure 1) simulates water flow, heat movement and the transport of solutes of variably saturated porous media in two and three dimensions (2D/3D) using various numerical and mathematical techniques. Many studies have evaluated the software and analyzed its potential for predicting water and nutrient movement for various drip irrigation methods [37,47].

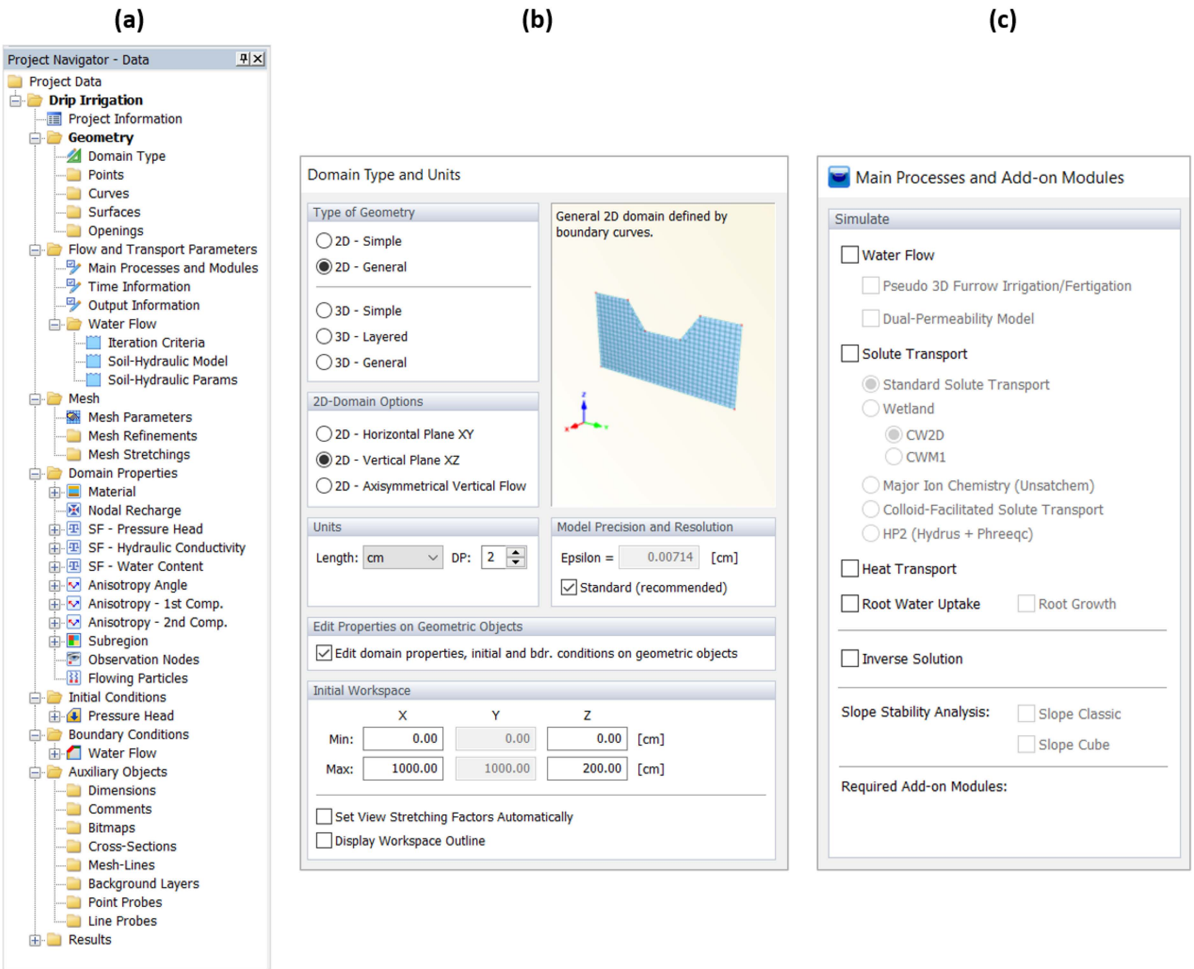

Figure 1. The Windows-based HYDRUS 2D/3D model software package. (**a**) Project navigator—data (interface), (**b**) domain types (2D/3D) and (**c**) main simulation modules.

A general schematic presentation of the transport domain of a -drip-irrigated tree with the main hydrological fluxes is shown in Figure 2a,b which also describes the main modules of the HYDRUS program for the simulation of these fluxes. The water flow module includes the saturated and unsaturated water flow and incorporates various models for the estimation of soil hydraulic properties. A sink term accounting for water uptake by plant roots is also included. For the heat and solute transport modules, HYDRUS uses convection–dispersion-type equations. The heat transport equation considers movement by conduction as well as convection with flowing water. The governing flow and transport equations are solved numerically using Galerkin-type linear finite element schemes. The inverse optimization is also included in the HYDRUS program which is an indirect approach for estimating the unsaturated soil hydraulic and/or solute transport parameters from transient flow and/or transport data [48]

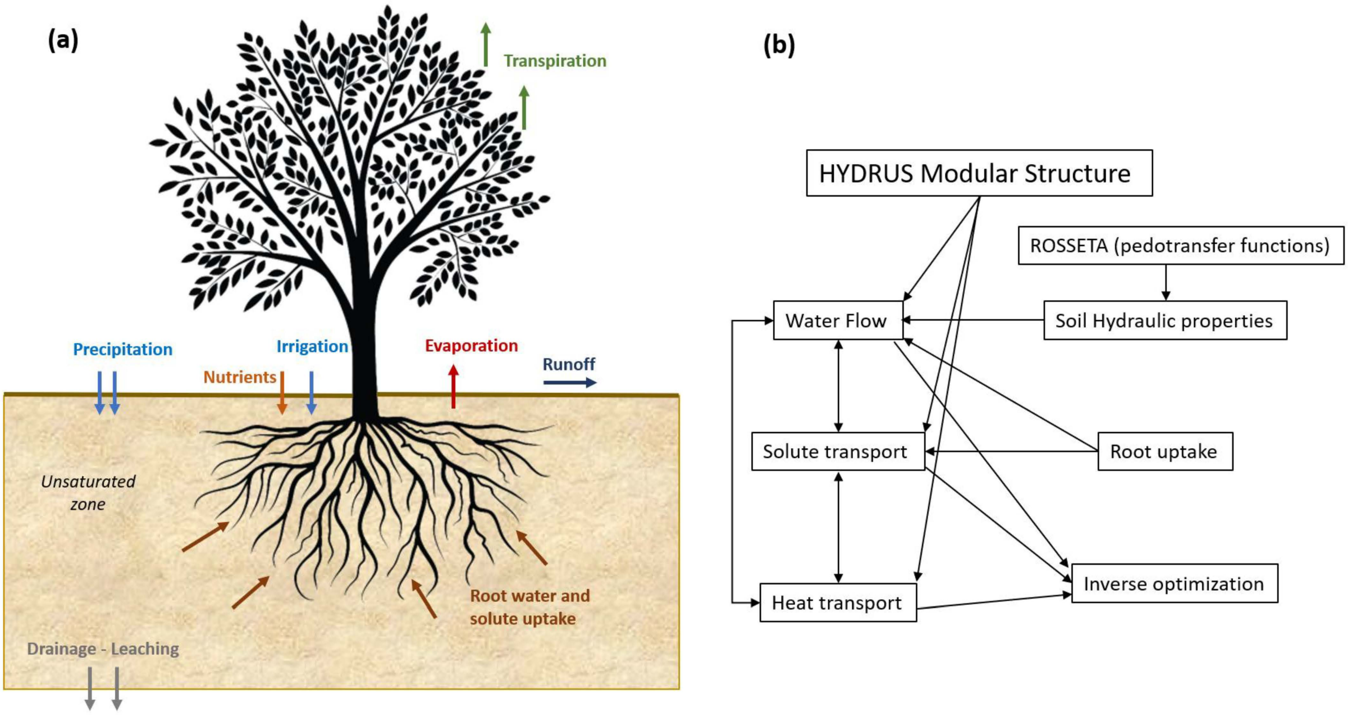

Figure 2. (**a**) Schematic of the main water and solute fluxes and (**b**) schematic of the HYDRUS modular structure.

The HYDRUS 2D/3D software numerically solves the Richards' equation (Equation (1)) for both saturated and unsaturated water flow using convection/dispersion equations for heat and solute transport [14].

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[K(h)\frac{\partial h}{\partial y}\right] + \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - S \quad (1)$$

where θ is the volumetric water content of the soil [$L^3\ L^{-3}$], t is time [T], K is the hydraulic conductivity [LT^{-1}], h is the soil water pressure head [L], x and y are the horizontal spatial coordinates [L], z is the vertical spatial coordinates [L] and S is the sink term representing root water uptake [T^{-1}]).

The sink term S in Equation (1) represents the volume of water removed per unit time from a unit volume of soil by the plant water uptake. Feddes [49] defined S as:

$$S(h,z) = a(h)\cdot S_{max}(h,z) \quad (2)$$

where the water stress response function $\alpha(h)$ is a prescribed dimensionless function of soil water pressure head ($0 \leq \alpha \leq 1$), S_{max} is the maximum possible root water extraction rate when soil water is not a limiting factor [$L^3\ L^{-3}\ T^{-1}$] and z is soil depth [L].

Soil hydraulic properties are calculated using the water retention function and hydraulic conductivity described by the van Genuchten–Mualem constitutive relationship [50,51]:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{\left[1+(\alpha h)^n\right]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad (3)$$

$$K(h) = K_s {S_e}^l \left[1 - \left(1 - {S_e}^{1/m}\right)^m\right]^2 \quad (4)$$

where θ_s is the saturated water content (L^3L^{-3}); θ_r is the residual water content (L^3L^{-3}); a (L^{-1}), m and n are empirical parameters that determine the shape of the soil water retention curve where $m = 1 - 1/n$ and l is the shape parameter; K_s is the saturated hydraulic conductivity (LT^{-1}) and S_e is the relative saturation (dimensionless) and is defined as:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (5)$$

The non-reactive solute transport in a homogenous medium is described by the governing advection–dispersion equation [52]:

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial c}{\partial x_i}\right) - \frac{\partial q_i c}{\partial x_i} \quad (6)$$

where θ is the volumetric water content; c is the solute concentration in liquid phase, ML^{-3}; t is the time, T; x_i and x_j (i, j = 1, 2, 3) are the spatial coordinates L; q_i (i = 1, 2, 3) are the water fluxes in three directions L T^{-1} and D_{ij} is the hydrodynamic dispersion coefficient tensor L^2 T^{-1}.

3. Citrus Trees

Citrus is recognized as a particularly important horticultural crop for the global agricultural sector as there are 140 countries that produce citrus [53]. Citrus trees produce fruits, including important crops such as oranges, lemons, grapefruits, pomelos and limes. Globally, citrus occupies 10,072,197.00 ha of agricultural land and reached 158,490,986.00 tons in 2020 [2]. Most of the citrus growing areas are exposed to dry and hot summer weather. The vast majority of citrus crops in these areas are oranges (56%), with the remainder distributed among mandarins (28%), lemons and limes (15%) and grapefruit (1%) [2]. Citrus irrigation and nutrient management are critical, especially in areas of water scarcity. Inadequate quantities of irrigation water or poor-quality water are factors that negatively affect citrus tree productivity and fruit quality. Regarding citrus fertilization, nitrogen is the key nutrient The increased use of nitrogen fertilizers in citrus results in nitrate leaching from the root zone and is a potential source of groundwater contamination [11]. Therefore, optimal irrigation and fertilization scheduling in citrus production are major challenges to the control of water and nitrogen losses below the root zone [54]. Therefore, efficient simulation models such as HYDRUS 2D/3D have become valuable tools for studying water dynamics and solute transport through the soil profile to design proper irrigation and fertigation systems for citrus cultivation [55].

3.1. HYDRUS 2D/3D Model Performance in Citrus Trees

There are many reasons as to why it is necessary to evaluate the performance of numerical models. A primary objective is to assess how well the model fits the observed data by adjusting model parameter values (calibration—validation), then the ability of the model to reproduce the historical and future behavior of agricultural/hydrologic systems and finally to compare current modelling efforts with previous studies [56]. In general, models such as HYDRUS 2D/3D have proven very useful for simulating conditions that are too expensive or technically impossible to test under field conditions. For citrus trees, the HYDRUS 2D/3D model has been used to simulate soil water dynamics and solute transport under both field conditions and more controlled experimental conditions (lysimeter).

In the lysimeter study by Phogat et al. [11], the model was calibrated using water content and drainage measurements under an orange tree. Simulations were also performed to evaluate nitrate leaching and fertigation management effects. Moisture content distributions and leaching rates predicted by HYDRUS 2D/3D agreed well with measured values in the lysimeter. The performance of the model was robust, as indicated by the statistical measures used in the study.

Experiments under field conditions used HYDRUS 2D/3D to predict seasonal water, salt and nitrate dynamics in citrus. Statistical comparisons of measured values with modeling results showed a consistent performance of the model [57]. In addition, Phogat et al. [57] observed discrepancies between predicted and observed nitrate–nitrogen ($NO3^-$-N) and soil solution salinity (ECsw) concentrations (mean absolute errors within acceptable limits). This is likely due to the assumption of a constant boundary flux at the surface during a given daily time step or because the model considers only a simple linear movement of nitrogen, rather than all complex processes (mineralization, denitrification, microbial interactions, etc.). Phogat et al. [58] claimed that most studies only evaluate a portion of the model and not its overall behavior. Therefore, they used eleven statistical measures to compare the values of water content, ECsw and $NO3^-$-N dynamics simulated by HYDRUS-2D with field-measured values obtained under drip-irrigated mandarins. The objective was to determine which set of statistical measures was most appropriate for evaluating model performance. They concluded that for the reliable evaluation of model performance in field applications, a combination of different statistical criteria must be included with an evaluation of absolute or relative volume error.

3.1.1. Findings Regarding the Design of Drip Irrigation Systems

In the literature, citrus cultivation is usually found growing under advanced fertigation systems that combine drip irrigation and fertilizer application to deliver water and nutrients directly to the roots of the plants. Therefore, there is a need to evaluate these systems because significant leaching of contaminants (especially nitrogen) can occur near drip lines. There are few studies investigating the importance of numerical modelling for the design and management of irrigation and fertigation systems in citrus, and even fewer studies using the HYDRUS 2D/3D model (Table 1). The first attempt to study the fate of nitrates in citrus using HYDRUS 2D/3D was conducted by Phogat et al. [11] in an experimental lysimeter. The design of the irrigation system used in this study, while quite common in fruit tree irrigation, has not been found in any other work where the drip irrigation system was simulated using the HYDRUS 2D/3D model. The emitters were placed on a circle 25 cm from the tree trunk equidistant from each other and the irrigation was modelled as a circular line source with a uniform water flux along the drip line. The other three works in the literature on simulating drip irrigation in citrus using HYDRUS 2D/3D were conducted under field conditions [55,57,58]. In these studies, irrigation water was supplied through a surface drip irrigation system, with drip lines placed 60 cm apart on either side of the tree line. Of the four studies with citrus trees, only Panigrahi and Sharma [55] made a comparison between the irrigation methods. They compared surface and subsurface drip irrigation and tested the distance of lateral lines from the tree trunk. It was found that the proper distribution of water in the root zone of citrus plants was possible when drip lines were placed at a distance 60 cm from the tree trunk (surface drip irrigation). In addition, subsurface drip irrigation produced higher yields by maintaining a relatively high water content in the root zone by placing the drip line at a depth of 30 cm. They also conclude that the distance of the irrigation line from the tree trunk depends on the age of the plant and the depth of the root system.

3.1.2. Findings Regarding Irrigation and Fertigation Strategies

In arid and semi-arid regions there is a growing need for irrigation methods that conserve water and maintain crop production. Traditionally, citrus plants are grown under advanced fertigation systems, and for this reason it is critical to keep nutrients in the root system, increase root uptake and avoid deep percolation. Deficit irrigation strategies can contribute to this end, stabilize yield and maximize water productivity. The main types of deficit irrigation in citrus production are sustained-deficit irrigation (SDI) and regulated-deficit irrigation (RDI). SDI is based on applying a specified level of constant water stress (a ratio of ET_C) throughout crop growth, without regard for the phenological period [59]. In RDI strategies, water stress is applied during specific crop stages. More specifically, the effects of RDI treatments depend on the phenological period in which the water restriction is applied. For instance, the application of RDI in citrus during period I (spring, flowering and fruit set) could diminish the final yield due to the fall of flowers and young fruits [60–62]. González-Altozano and Castel [63–65] carried out several RDI tests on an experimental orchard of '*Clementina de Nules*' citrus trees and they concluded that the application of RDI during period II (initial fruit enlargement, July–August) did not affect yield, fruit size or quality and allowed significant water savings. They also observed that water deficit during period III (final stages of crop development, end of summer–autumn) resulted in a decrease the fruit size.

In this context, using HYDRUS 2D/3D Phogat et al. [9] evaluated scenarios in which less irrigation water (50% and 75% of ETc) is applied. The results show that a higher uptake efficiency was achieved when less water was applied. In another study, Phogat et al. [53] evaluated certain scenarios that focused on reducing irrigation and N application by 10–20% through the growing season. These scenarios resulted in a reduction in N leaching and water drainage, but also in a decrease in N uptake and water uptake compared to normal practice. At the same time, salinity was increased. The main problem with these scenarios was that a reduction in plant water and N uptake would have a major impact on plant growth and yield. They also tested scenarios with a 10–50% reduction in irrigation in the second half of the growing season. They concluded that a 30% reduction in irrigation during this period was the best scenario, reducing both water and nitrate leaching and increasing crop N uptake compared to full irrigation. They found that further reductions in irrigation of 40% and 50% greatly reduced water and nitrate infiltration and also increased soil solution salinity (ECsw, dSm^{-1}) in the root zone to a level much higher than the tolerance threshold of the crop.

Other parameters studied with the HYDRUS 2D/3D model are related to the form of irrigation strategy in terms of time intervals and duration of irrigation/fertigation. Nitrate management and irrigation strategies also include increasing or decreasing the frequency of application. In a scenario by Phogat et al. [57], increasing the irrigation frequency with short irrigation events while maintaining the same irrigation volume had no effect on the deep percolation of water and nutrients. However, an increase in salinity was observed compared to traditional practices. Simulations in citrus examined the influence of application timing and showed that it did not have a large impact in a normal fertigation schedule with small and frequent N doses within an irrigation event in both pulsed and continuous irrigation scenarios [11,57].

3.2. Summary of HYDRUS 2D/3D Application in Citrus Trees

The application of the HYDRUS 2D/3D model to drip-irrigated citrus trees is not extensive enough to draw conclusions about the optimal irrigation scheme in terms of the number of laterals and drippers or the optimal position of the dripper (radial, deep). Only one study compares surface and subsurface irrigation and concludes that subsurface irrigation produced higher yields by maintaining relatively higher water content in the root zone. On the other hand, all HYDRUS 2D/3D studies on irrigation strategies in citrus show that deficit irrigation is a good agricultural practice to conserve water and maintain production. Although caution should be used when applying high water stress, there is a risk of increasing soil salinity. This risk also exists when the frequency is changed and when short irrigation events are applied. Otherwise, frequency does not affect other factors such as percolation, water and nutrients. It is also worth mentioning that due to the application of fertigation to citrus, the fate of nitrates in the soil is also studied, which has not been explored to a large extent in simulations with tree crops.

Table 1. Summary of HYDRUS 2D/3D simulations in citrus trees.

Research Report	Crop	Soil Type	Irrigation System [1]	Irrigation Treatment [2]	HYDRUS 2D/3D	Simulation Processes
Phogat et al. [11]	orange (lysimeter)	(0–60 cm soil depth): loamy sand (60–85 cm soil depth): sandy Loam (85–110 cm soil depth): sand	DI -on a circle and fertigation	Ip vs. Ic	2D	Water flow Root uptake Nitrate dynamics
Phogat et al. [57]	mandarin	(0–90 cm soil depth): sandy loam (90–150 cm soil depth): loam	DI -2 drip lines and fertigation	different schedules	2D	Water flow Root uptake Salinity and Nitrate dynamics
Panigrahi and Sharma [55]	mandarin	(0–40 cm soil depth): sandy loam (40–100 cm soil depth): sandy clay loam	SubDI vs. DI	-	2D	Water flow Root uptake
Phogat et al. [58]	mandarin	(0–90 cm soil depth): sandy loam (90–150 cm soil depth): loam	DI-2 drip lines and fertigation	-	2D	Water flow Root uptake Salinity and Nitrate dynamics

Notes: [1] SubDI: Subsurface Drip Irrigation; DI: Drip Irrigation. [2] FI: Full Irrigation; RDI: Regular Deficit Irrigation; SDI: Sustained Deficit Irrigation; Ip: Pulsed Irrigation; Ic: Continuous Irrigation.

4. Olive Trees

Olive cultivation is considered one of the most important and oldest agricultural activities. The most common olive varieties encountered are Arbequina, Wilsoni, Chemlali, Hojiblanca, Frantoio, Coratina, Leccino, Kalamata, etc. According to the FAO's statistics (2021), southern Europe produces about 60% of the world's olive production. In the past, olive trees (*Olea europaea L*) were mainly grown under rainfed conditions. However, in recent decades, due to climate change and increased crop water demands, olive producers have opted for irrigation to achieve optimal yields, using drip systems in most cases [66]. However, water limitations in the main olive-growing areas have led farmers to consider different adaptation strategies and irrigation systems. For example, many farmers apply deficit irrigation strategies to save water while maintaining crop profitability. The HYDRUS 2D/3D model is widely used in the scientific literature for the design and management of drip irrigation systems.

4.1. HYDRUS 2D/3D Model Performance in Olive Trees

Only four studies were found in the literature evaluating drip irrigation systems and strategies for olive trees using the HYDRUS 2D/3D model (Table 2). These studies only concern simulations of soil water content as no studies of nitrate–nitrogen ($NO3^-$-N) or soil solution salinity (ECsw) dynamics in olive trees have been conducted using this model. In their study, Egea et al. [67] found a good level of agreement between simulated and observed soil–moisture contents across all treatments and probe locations studied. However, they also found that model accuracy decreased when regulated deficit irrigation was considered compared to full irrigation treatments, which could be due to possible inaccuracies and oversimplifications in modeled root water uptake under drought conditions. The orchard used for the experiments and simulations by Egea et al. [67] was also used by Fernandes et al. [68] four years later. The RMSE and MAE values obtained from the comparison of measured and simulated soil water contents were similar to those reported by Egea et al. [67] calculated for full irrigation (RMSE: 0.035–0.050 m^3m^{-3} and MAE: 0.030–0.040 m^3m^{-3}), and slightly larger for deficit irrigation treatments (RMSE: 0.058–0.083 m^3m^{-3} and MAE: 0.047–0.075 m^3m^{-3}). Therefore, both studies claim that the simulations with the HYDRUS 2D/3D model are considered acceptably accurate. Autovino et al. [22] investigated the performance of the HYDRUS-2D numerical model for predicting soil water content and transpiration fluxes in an olive orchard irrigated with two different irrigation systems. The measurements of the midday stem water potential were also used for the calibration of the relative transpiration simulated by the model. The statistical analysis shows that the patterns of soil water contents generated by the model matched well with those measured in the experimental field. In addition, the model was also capable of estimating actual transpiration with acceptable RMSE values for both years of the experiment. Consequently, HYDRUS 2D/3D seems to be a suitable model to solve the water mass balance of olive trees under Mediterranean climate conditions. Carlos et al. [69] also wanted to test the efficiency of the model under desert conditions, namely in an olive orchard in Chile. The efficiency of the model was evaluated by comparing model simulations with observations of volumetric water content and electrical conductivity in pores with five frequency domain reflectometry (FDR) sensors installed in the soil profile. They concluded that HYDRUS 2D/3D represents the variations in volumetric water content in olive trees in the desert with acceptable accuracy. However, the same conclusion was not reached for the simulation of electrical pore conductivity under the same conditions.

4.1.1. Findings Regarding the Design of Drip Irrigation Systems

Surface irrigation is used in all four olive orchard studies with HYDRUS 2D/3D. The studies focused on the design of drip irrigation systems by evaluating the impact of the number of drip laterals and drippers. Egea et al. [67] evaluated the correctness of irrigation design in an experimental olive orchard by analyzing the simulated soil water balance components. In a HYDRUS 2D simulation scenario they reduced emitter discharge rates by half and doubled the number of drippers by adding another irrigation line. They found that reducing emitter discharge by doubling the number of drip lines did not cause differences in soil water balance components (soil water, evapotranspiration and drainage). A more recent study by Fernandes et al. [68] reached the same conclusion. They also studied the effects of using one or two drip irrigation pipes per tree row. The results showed no effect of irrigation with one or two drip lines per tree row on leaf water potential, stomatal conductance, growth and fruit production. We must emphasize here that both studies were conducted in high density olive orchards and conclude that there are no benefits from using two drip irrigation laterals instead of one. Another comparison between two different irrigation systems was conducted by Autovino et al. [22]. They used HYDRUS 2D to predict soil water dynamics and transpiration fluxes in an olive orchard where a single drip lateral per plant row was installed symmetrically on both sides of each tree, compared to an irrigation system that distributes water over the entire soil surface. They found that with the second irrigation system, the distribution of water content in the soil was more uniform than with a single drip system. In addition, because of the second irrigation system (uniform irrigation throughout the field), the plants may have developed a different root distribution and thus a locally altered water uptake. The lack of knowledge about the temporal patterns of the active root system does not allow further speculation.

4.1.2. Findings Regarding Irrigation Strategies

The HYDRUS 2D/3D model was also used to simulate the components of soil water balance (irrigation, precipitation, evapotranspiration, water uptake by roots, drainage and soil storage) to evaluate irrigation management in olive orchards under different irrigation regimes. Simulations in drip-irrigated olive orchards show that differences in soil volume and soil surface area moistened by irrigation are not sufficient to affect the water components studied [67,68]. Egea et al. [67] found that the differences in deep percolation between full irrigation and deficit irrigation treatments were mainly caused by a rainfall event towards the end of September and not by the irrigation strategy. Therefore, deficit irrigation is a safe management option because it does not significantly affect the components of the soil water balance. However, consideration must be given to the stage of vegetative growth at which is it implemented. Not applying irrigation can put the plant under severe stress at the II stage of vegetative growth (flowering in mid-May) when it is sensitive to water stress. The application of deficit irrigation (50% of ETc) during the period from mid-June to late August allows the measured midday water potential of the stems to always remain below the threshold for mild water stress [22]. Fernandes et al. [68] showed in their results that daily maximum leaf stomatal conductance, shoot growth and leaf area were greater during full irrigation than during regulated deficit irrigation (45% of ETc). Despite these differences, deficit irrigation did not cause differences in either fruit or oil yields. They also concluded that a deficit irrigation strategy minimized water losses with respect to drainage, compared to full irrigation.

Other factors that affect soil water components and play a key role in designing the irrigation strategy are the frequency and timing of the application. Of the three studies conducted in olive orchards using HYDRUS 2D/3D, only Egea et al. [67] evaluated the effects of daytime versus nighttime irrigation and irrigation frequency on seasonal water balance components. They found that in the case of full irrigation, daytime irrigation resulted in slightly higher water losses through deep percolation than nighttime irrigation and that, for the same irrigation amounts, root zone pressure head decreased as irrigation frequency increased. Therefore, an irrigation strategy should also conclude the adjustment of these factors for the treatment applied.

4.2. Summary of HYDRUS 2D/3D Application in Olive Trees

For olive trees only four papers were conducted to simulate drip irrigation using the HYDRUS 2D/3D model. All studies concerned surface irrigation, and some tests were performed with an increase in laterals and drippers, keeping the amount of water supplied to the trees constant. The results show that the number of laterals has no effect on soil water components. In olive trees, it also showed that deficit irrigation has no effect on the components of water balance and fruit yield, but the absence of irrigation in the II stage of vegetation can cause severe stress to the plant. Therefore, deficit irrigation is a safe strategy that allows minimizing water losses due to drainage. One study also examined the effects of irrigation timing and frequency and found that increasing irrigation frequency can reduce the pressure head in the root zone. Salinity and nitrate dynamics have not yet been studied, mainly because fertigation is not usually applied to olives. However, fertilization is applied in winter, so the fate of nitrates in soils during winter rains must also be studied.

Table 2. Summary of HYDRUS 2D/3D simulations in olive trees.

Research Report	Crop	Soil Type	Irrigation System [1]	Irrigation Treatment [2]	HYDRUS 2D/3D	Simulation Processes
Egea et al. [67]	olive arbequina	(soil depth 0–40): sandy loam	DI-1 vs. 2 drip lines	FI: 100% ETc	2D	Water flow Root uptake
		(soil depth 40–100): sandy clay		RDI:		
Autovino et al. [22]	olive nocellara del Belice	(homogenous soil depth): silty clay loam	DI-1 drip line vs. total surface irrig.	FI: 100% ETc	2D	Water flow Root uptake
				RDI: 50% ETc		

Table 2. *Cont.*

Research Report	Crop	Soil Type	Irrigation System [1]	Irrigation Treatment [2]	HYDRUS 2D/3D	Simulation Processes
Fernandes et al. [68]	olive arbequina	(soil depth 0–60): sandy	DI-1 vs. 2 drip lines	FI: 100% Etc SDI: 45% Etc RDI: 45% Etc	2D	Water flow Root uptake
Carlos et al. [69]	olive	not listed	DI-2 drip lines	-	2D	Water flow Root uptake

Notes: [1] SubDI: Subsurface Drip Irrigation; DI: Drip Irrigation. [2] FI: Full Irrigation; RDI: Regular Deficit Irrigation; SDI: Sustained Deficit Irrigation; Ip: Pulsed Irrigation; Ic: Continuous Irrigation.

5. Avocado Trees

The avocado is becoming one of the most important tropical crops for the world market. In Europe, production and consumption of avocados have increased dramatically in recent decades [70]. The most widespread varieties are Hass, Pinterton, Lamb Hass, Carmen Hass, Stewart, Holiday, Pryor, Opal, Fuerte, Zutano, etc. The increase in avocado consumption and spread to new markets around the world, in countries where avocado was not traditionally consumed before, has led to local production in new areas such as the Mediterranean region [71]. This is because locally grown fruits can generally offer consumers a higher quality in terms of taste, nutritional value, and organoleptic properties, as well as better prices [72,73]. However, choosing the right location for planting avocados should be carefully considered to reduce the likelihood of future problems. Regarding soil conditions, important parameters are pH, carbonate content, soil drainage capacity and salinity [74]. In addition, avocados are quite demanding in terms of water compared to other tree crops. The water requirements of avocado trees depend on various factors such as the age of the tree, the soil type and climatic conditions. Therefore, new irrigation techniques that combine irrigation monitoring and simulation will be useful tools to conserve water, mitigate leaching and control soil salinity while ensuring good tree yield.

5.1. HYDRUS 2D/3D Model Performance in Avocado Trees

To date, there are only two research studies in the literature that use the HYDRUS 2D/3D model in irrigated avocado trees [75,76]. The two studies evaluated the effects of irrigation with freshwater (FW) and wastewater (WW). The simulated results did not aim to reproduce real field conditions but rather focused on soil hydraulic properties, their difference in drip irrigation with FW and WW and their effects on water uptake and transpiration.

5.1.1. Findings Regarding the Design of Drip Irrigation Systems

In both studies of drip irrigation of avocado orchards, the irrigation system in the field consisted of two drip lines per row placed 25 cm on opposite sides of the trunk, with drippers delivering 1.6 L/h [76] discharge and 2 L/h [75], respectively, 50 cm apart. However, Assouline et al. [76], in order to find the best combination between irrigation management and design when using WW, conducted the following tests: (a) applying different irrigation rates (halving or doubling the drip rate) for the same (shorter or longer) duration at the same irrigation dose; (b) increasing the number of lateral drip lines per tree row from 2 to 4, 15 and 65 cm from the tree on both sides and (c) changing the irrigation frequency from one irrigation every 2 days to daily irrigation. The different combinations are described in Table 3. The effects of these experiments were expressed, in terms of changes in soil hydraulic properties and plant water uptake which is also related to yield. The results show that increasing the number of driplines per row increases actual transpiration in both FW and WW irrigation, and significantly reduces the difference between the two treatments, mitigating the effects of WW irrigation. The authors also pointed out that the above results could also be achieved by increasing the number of drippers per row (reducing the distance between them) or by using concentric loops of driplines around the trunk.

5.1.2. Findings Regarding Irrigation Strategies

The irrigation treatments tested on avocado trees using the HYDRUS 2D/3D model are: (1) using wastewater versus freshwater treatments, (2) application of different irrigation rates (changing discharge and duration) and (3) changing irrigation frequency. Assouline and Narkis [75] used the axisymmetric vertical flow solution (flow variables: i.e., velocity and pressure, do not vary with angular coordinate θ) from HYDRUS 2D to create a representation of water content distribution below the dripper in an FW and a WW irrigation soil profile. The results indicate that although a similar amount of water was applied in both treatments, the total wetted volume in the WW irrigation soil was smaller and more saturated. This behavior was often explained by the hydrophobicity of soil caused by the WW application. In addition, WW was observed to have a negative effect on soil hydraulic properties (saturated hydraulic conductivity, sorptivity, cumulative infiltration and evaporation were consistently lower).

On the one hand, long-term use of WW for irrigation can degrade soil properties which in turn affects crop water uptake and leads to lower yields. On the other hand, there is a need to treat and recycle wastewater and use it whenever possible and appropriate to conserve freshwater, especially in areas of water scarcity. For this reason, Assouline et al. [76] studied the effects of mixing WW with FW. Four water qualities resulting from mixing FW and WW in different ratios for irrigation of an avocado orchard were considered. In the simulation study the effects of salinity and related osmotic potential on root uptake and transpiration were not considered, since the objective was not to reproduce real field conditions, but to focus only on the aspect of soil hydraulic properties in drip irrigation with FW and WW. Transpiration in FW-irrigated soil is about 10% higher than in WW-irrigated soil. In addition, the results at all soil depth show that the infiltration capacity of the soil decreases as the percentage of WW in the irrigation water increases. Mixing FW with WW (a higher proportion of FW) allows the use of WW without affecting the hydraulic properties of the soil, which become apparent after a few years of irrigation, and without significantly affecting plant uptake and growth. The advantages of mixing are also the reduction of freshwater demand, the use of water with nutrients and the minimization of pollutant leaching into waterways [77].

As mentioned earlier, Assouline et al. [76] evaluated irrigation rate and frequency for drip-irrigated avocado trees using the HYDRUS 2D model. They conclude from their results that there is no gain in increasing the dripper discharge if the current arrangement of the two drip lines and frequency remain the same (every 2 days). However, the use of lower discharge increases transpiration and decreases the difference between FW and WW irrigated soils. On the other hand, increasing the irrigation frequency to daily irrigation had a significant negative effect, especially on WW irrigated soil. The difference between actual transpiration in the FW- and WW-irrigated soils is maximum at this irrigation frequency, regardless of the amount of drip water used.

5.2. Summary of HYDRUS 2D/3D Application in Avocado Trees

The conclusion of the two studies is that long-term irrigation with WW negatively affects the hydraulic properties of soil and affects the transpiration and yield of the tree. However, Assouline et al. [76] indicated that the use of drippers with lower discharge rates combined with an increase in the number of driplines which increases the wetted area per tree tends to reduce the negative effects. This can also be accomplished by increasing the number of drippers per line or by using concentric loops of driplines around the trunk. The approach of more drippers per line or the use of concentric driplines should be further investigated.

Another gap in the studies is that while the effluent retains increased salinity, there are no simulations for salt leaching or other nutrients. In addition, the two studies conducted on avocado trees do not compare simulation results with field observations. The above information is based on results of laboratory experiments conducted on disturbed soil samples. Therefore, they cannot fully represent the behavior of the soil profile at the field scale. This could be a challenge for future studies. Additionally, for future research it would be of interest to examine the fate of mineral and organic loads of applied wastewater in soil with the help of Hydrus submodules.

Table 3. Summary of HYDRUS 2D/3D simulations in avocado trees.

Research Report	Crop	Soil Type	Irrigation System [1]	Irrigation Treatment [2]	HYDRUS 2D/3D	Simulation Processes
Assouline and Narkis [75]	avocado	(homogenous soil depth): clay	2 drip lines; 2.0 L/h	FW	2D	Water flow Root uptake
				WW		
Assouline et al. [76]	avocado	(homogenous soil depth): clay	2 drip lines; 48 h; 3.2 L/h	FW	2D	Water flow Root uptake
			2 drip lines; 48 h; 1.6 L/h			
			2 drip lines; 48 h; 0.8 L/h	2/3 FW—1/3 WW		
			2 drip lines; 24 h; 1.6 L/h			
			2 drip lines; 24h; 0.8 L/h	1/3 FW—2/3 WW		
			4 drip lines; 24 h; 0.8 L/h			
			4 drip lines; 48 h; 1.6 L/h	WW		
			4 drip lines; 48 h; 0.8 L/h			

Notes: [1] SubDI: Subsurface Drip Irrigation; DI: Drip Irrigation. [2] FI: Full Irrigation; RDI: Regular Deficit Irrigation; SDI: Sustained Deficit Irrigation; Ip: Pulsed Irrigation; Ic: Continuous Irrigation; FW: freshwater irrigation; WW: wastewater irrigation.

6. Deciduous Fruit and Nut Trees

Fruit trees are divided into two groups, evergreen and deciduous, and most fruit trees are classified as deciduous. Deciduous fruit trees and nut trees include those that bloom in the spring and summer and lose all their leaves in the fall. These trees remain bare during the winter months and require the cold temperatures to produce leaves and flowers in the spring [78]. Major fruit crops include apples (*Malus sylvestris*), apricots (*Prunus armeniaca*), cherries (*Prunus sp.*), figs (*Ficus carica*), peaches (*Prunus persica*), pears (*Pyrus communis*), plums (*Prunus sp.*) and prunes (*Prunus domestica*). Important nut crops are almonds (*Prunus amygdalus*), filberts (*Corylus avellana*), pecans (*Carya illinoensis*) and walnuts (*Juglans regia*). All these crops are grown mainly in temperate zones [79]. Irrigation is critical to the efficiency of deciduous trees because most of them can consume large amounts of water when evaporative demand is high. Therefore, improving irrigation water use in deciduous and nut trees is also essential due to water scarcity and the risk of groundwater contamination from leachate from irrigated fields [80].

6.1. HYDRUS 2D/3D Model Performance in Deciduous Fruit Trees and Nut Trees

Twelve studies were found in the literature using the HYDRUS 2D/3D model to simulate water dynamics under deciduous trees (Table 3). The first simulation of drip irrigation in a deciduous tree was also the first simulation conducted on trees using the HYDRUS 2D/3D model and was conducted on jujube trees by Yao et al. [81]. In deciduous trees (apple trees) were also the first studies to simulate drip irrigation in perennial crops using the 3D model of the HYDRUS 2D/3D package [82,83].

In the first study by Yao et al. [81], the goodness of fit between simulated and measured values of volumetric soil water content was evaluated by using the root-mean-absolute error (RMAE). The results show that the RMAE values for water dynamics in all soil layers below the drip tube indicate that the model can perform well throughout the growing season. Subsequently, many studies of -drip-irrigated deciduous trees successfully simulated changes in soil water content at various distances from the emitter, times and soil depths using HYDRUS 2D. Phogat et al. [9], Phogat et al. [84] and Phogat et al. [85] matched the simulated soil water content well with the weekly measured neutron probe values for both pulsing and continuous irrigation treatments in an almond orchard. Measured mean soil water salinity (ECsw) also agreed well with predicted values, for both pulsed and continuous drip systems. In the study by Phogat et al. [84], they also observed that the root-mean-squared error (RMSE) value between the weekly measured and simulated moisture content decreased throughout the domain when only a soil depth of 30 cm was considered, where root density is highest in almonds. This indicates a good prediction of seasonal soil moisture distribution and plant water uptake. Yang et al. [86] calibrated and validated the HYDRUS 2D model using soil water content and transpiration data. Simulation results for both calibration and validation showed that average simulated soil water values (within water volume) matched those measured once, especially during the irrigation period. In addition, simulated transpiration matched the measured data quite well in both years. According to Janssens et al. [87], soil water potential (Ψsoil) can also be successfully simulated using HYDRUS 2D. Only when the observed Ψsoil increased above −20 kPa did the observed Ψsoil not match the calculated one, possibly due to the limitations of the Watermark sensors in measuring the soil water potential in the wet range, above −20 kPa. This suggests that positioning the sensors near the irrigation drippers should be avoided, as mentioned in a previous chapter.

Xi et al. [88] and Nazari et al. [89] showed that HYDRUS-2D also provided a good estimate of soil water content under subsurface drip irrigation in a P. tomentosa plantation and in an apple orchard, respectively. In addition, Xi et al. [88] agree with Phogat et al. [84] that the top layer of 30 cm provides more robust simulations of water content and consequently better predictions of tree growth responses to soil water.

Domínguez-Niño [82,83] were the first to use HYDRUS 3D to simulate soil water dynamics in drip-irrigated trees. They pointed out that for the simulation of an orchard, it is more interesting to use HYDRUS-3D than HYDRUS-2D because it solves the transport problems on all three axes simultaneously and provides more realistic calculations of the soil water distribution around the dripper. Special attention was paid to the source of the soil hydraulic parameters. Simulations parameterized with the ROSETTA approach were compared with others parameterized with the HYPROP + WP4C approach. ROSETTA is a software package that evaluates pedotransfer functions that use neural network models to predict soil hydraulic parameters from soil texture and related data for the van Genuchten–Mualem model [51]. The results showed that the best agreement with soil moisture measurements was obtained with simulations parameterized with HYPROP + WP4C.

6.1.1. Findings Regarding the Design of Drip Irrigation Systems

Most of the studies in deciduous fruit trees and nut trees using the HYDRUS 2D/3D model were conducted under surface drip irrigation with one or two irrigation lines, although no comparison was made between irrigation systems and designs. Two of the studies on deciduous trees examined soil wetting patterns under subsurface drip irrigation [87,88]. According to many irrigation studies, compared to surface drip irrigation (DI), subsurface drip irrigation improves the delivery of water and nutrients directly to the root zone while significantly reducing water losses through evaporation [39,90,91]. Nazari et al. [89] try to determine the optimal location of emitters (radial and deep) in an irrigated apple orchard using the HYDRUS 2D model. Their results show that for maximum use of available water by plant roots, it is better to install emitters at a distance (60 cm and 50 cm) from the tree trunk.

Another important parameter in the design of a modern irrigation system in the context of smart agriculture is accurate monitoring. The optimal position of the sensors must show significant variation and should be sensitive to irrigation. To ensure reliable monitoring, several publications on drip irrigation simulation using the HYDRUS 2D/3D model investigate the position of the measuring devices (e.g., tensiometers and sensors) in deciduous trees, especially with respect to the drippers. No similar studies have been published for olive and citrus trees. Only Autovino et al. [22] mentioned drip-irrigated olive trees in their study and that the detection of soil water status requires the correct positioning of the measurement sensors to determine the soil water content values representative of the whole root zone. Janssens et al. [87] used the HYDRUS 2D model in their study to calculate soil water potential in an irrigated pear orchard to evaluate the extent to which Ψ_{soil} observations obtained with soil water potential sensors in irrigated pear orchards can be related to numerical calculations of Ψ_{soil} distribution. The results of this study suggest that sensor positioning near the irrigation drippers should be avoided to prevent overestimation of Ψ_{soil} and inaccurate irrigation scheduling. On the other hand, Yang et al. [86] recommended that sensors should be placed at a depth of 10 cm and at a distance of about 15 cm from the dripper for surface drip irrigation. Their study was conducted in *P. tomentosa* plantations using the HYDRUS 2D model. Their objective was to determine the appropriate location of soil–water potential (SWP) sensors for a representative SWP. Populus *tomentosa* plantations are not fruit or nut trees, but irrigation is a critical factor for tree growth. In this study, different locations of tensiometers around the dripper and the tree were investigated combining field experiments and numerical simulations while considering indices of soil water, root distribution, tree growth, plant physiology and irrigation scenarios. Two other studies conducted in an apple orchard by Domínguez-Niño et al. [82] and Domínguez-Niño et al. [83] concluded that the recommended sensor locations could be a combination of sensors near the vertical of the drip and other sensors in the middle between adjacent drippers, both at a 30 cm depth. The results of the last two studies are more robust because the HYDRUS 3D model was used. The HYDRUS 3D model provides more realistic calculations of soil water distribution around the dripper in the orchard compared to HYDRUS 2D because it solves the transport problems on all three axes simultaneously. For example, a 3D representation allows consideration of neighboring drippers distributed along an irrigation dripline and at greater distances from neighboring driplines. A recent study conducted in a pistachio orchard aimed to determine the optimal measurement position for soil apparent electrical conductivity (ECa) using an electromagnetic sensor (EMI) to monitor soil salinity (ECe). Two case studies were simulated using HYDRUS 2D, one with high initial soil salinity and low salinity irrigation water, and one with low initial soil salinity and high salinity irrigation water. The analyses of these two case studies show that a reliable EMI measurement distance from the dripline was about 100 cm in the case of low salinity irrigation in saline soils and close to the dripline in the case of high salinity irrigation [92]. The results obtained from these studies are specific to the case studies considered. The optimal location for measurement may differ for different soils, crops and/or irrigation scenarios.

6.1.2. Findings Regarding Irrigation Strategies

As with olive, avocado and citrus, research on irrigation strategies/treatment is as important as research on irrigation systems and designs to optimize productivity and minimize losses of limited irrigation water. Phogat et al. [84] were the first to conduct HYDRUS-2D simulations on field data recorded for a deciduous tree (almond tree) to evaluate daily variations in water fluxes under normal and stress conditions. The treatments studied for the almond tree were a) full irrigation (100% ETc) by pulsed irrigation (FIp), b) sustained deficit irrigation (65% ETc) by pulsed irrigation (SDIp) and c) full irrigation (100% ETc) by continuous irrigation (FIc). The results obtained by the above HYDRUS-

2D simulation showed that the efficiency of water uptake was significantly higher under sustained deficit irrigation (SDIp), while the additional water supply under full irrigation (FIp and FIc) resulted in water losses due to drainage. In addition, they observed that simulated salinity distribution was higher under SDIp, but well below the threshold for salinity in almond cultivation. The tolerance of almonds to water stress is also reflected in water productivity values. Similar conclusions were reached by Janssens et al. [87] who applied two Sustained Deficit Irrigation treatments in a drip-irrigated pear orchard, one at 80% of ETc and one at 50% of ETc. They observed that at an irrigation rate of 80% ETc, the wet area of the soil extended to the entire irrigated side of the tree to a depth of 70 cm, in contrast to irrigation at a rate of 50% ETc where the wetting front remained concentrated around the drippers. When applying water stress treatments, attention must be paid to tree growth and productivity in addition to environmental impacts (water and nutrient losses due to drainage). According to Xi et al. [88], soil water availability is directly related to tree growth and productivity. In their study, two treatments were applied: a rainfed control treatment in which no irrigation occurred and a treatment in which trees were irrigated when the average soil water potential (SWP) reached −25 kPa at a depth of 20 cm from the dripper. In both treatments, water availability in the soil increased with depth and was significantly higher in the treatment with 25 kPa irrigation than in the treatment without irrigation, but this difference was very small in the soil below a depth of 90 cm. Despite the high water availability at a 90 cm depth, the trees still suffered from growth loss when the soil was dry at the surface.

Phogat et al. [9], Phogat et al. [84] and Phogat et al. [85] used the finite element numerical model HYDRUS 2D to evaluate the effects of pulsed irrigation on water balance and salinity distribution in the soil. Pulsing irrigation is the application of daily irrigation in a phase of one hour of irrigation and one hour of break. The results of the first study [85] show that pulsed irrigation with a higher discharge rate (3.87 l/h) resulted in a similar water and salinity distribution in the soil compared to continuous irrigation with a low discharge rate (2 l/h). They also observed that simulated seasonal water uptake was slightly higher with pulsed irrigation, but soil storage was slightly higher with continuous irrigation. Studies like this are important in accurately calculatinig the leaching fraction required to flush salts from the root zone. More specifically, in their extensive research on the design of a drip irrigation system for almond trees, Phogat et al. [9] concluded that: a) soil texture, initial water content and duration of irrigation are important factors in the movement and distribution of water and solutes within the soil profile; b) pulsing has little effect on the leaching percentage and salt removal in coarse textured soils; c) it is possible to control the wetted volume of a soil by an appropriate combination of drip discharge and timing of irrigation and d) initial flushing of salts from the plant root zone can be achieved in surface drip irrigation with continuous heavy irrigations early in the irrigation season, regardless of the method used. However, it is not clear from these studies what the long-term effects of pulsed irrigation are. Therefore, in the same almond orchard, Phogat et al. [84] used HYDRUS 2D/3D on field data recorded over one growing season. Regarding the design of the irrigation system, they reached the same conclusions as in the previous studies. That is, high discharge rate pulsed irrigation could be a viable alternative to slow discharge continuous irrigation in soils with a coarse texture. This study attempted to further investigate the effects of pulse irrigation on water uptake, drainage and water productivity by combining it with deficit irrigation strategies. The results of this study were analyzed in detail in a previous paragraph. Nazari et al. [89] also concluded that dripper discharge and duration of irrigation are very important parameters for irrigation strategies. Their results show that by reducing the emitter discharge and increasing the irrigation duration (while maintaining the same water volume), the root water uptake increases. The irrigation rate was also studied by Hardie et al. [93]. This study was also conducted on an irrigated apple orchard, where a low irrigation rate treatment was irrigated for 45 min, while the high irrigation rate treatment was irrigated for 90 min. Modeling showed that irrigation tended to wet the soil near the surface between emitters at both rates. In addition, there was no significant difference in nitrate concentration after irrigation at both the high and low irrigation rates. One treatment that has also been studied in drip-irrigated deciduous trees using the HYDRUS 2D model, is saline irrigation [92]. Two case studies were simulated: (a) low salinity soil irrigated with high salinity irrigation water and (b) high salinity soil irrigated with low salinity water. The two different treatments were applied to determine the optimal location for the electromagnetic sensor (EMI) for soil salinity measurements, which was analyzed in a previous chapter.

6.2. Summary of HYDRUS 2D/3D Application in Deciduous Fruit Trees and Nut Trees

In the HYDRUS 2D/3D studies on deciduous fruit trees and nut trees, different irrigation systems and irrigation schemes are used. Most of them use surface drip irrigation with one or two irrigation laterals, while two studies investigate soil-wetting patterns under subsurface drip irrigation (Table 4). Although no comparison was made between irrigation systems and designs, one study of apples with subsurface drip irrigation attempted to determine the optimum distance to install emitters from the tree trunk. One factor in irrigation system design that has been considered only for deciduous trees is the optimal location of monitoring sensors. Conclusions from the studies are not clear on the monitoring position, as some studies argue that sensors should not be near the drippers, while others argue the opposite. However, there are also studies that suggest a combination of positions for the sensors, and this is probably the safest for accurate monitoring. As for deficit irrigation, the conclusions for deciduous trees are similar to those for citrus and olive trees. Compared to full irrigation treatment, where water uptake efficiency is higher, water losses through drainage are lower and salinity distribution is higher. There are different conclusions for the influence of irrigation frequency, especially for irrigation. Pulsing irrigation with a high discharge rate could be a viable alternative to continuous irrigation with slow discharge to control the wetted volume of a soil. In addition, the rate of irrigation treatment (e.g., reducing the emitter discharge and increasing the duration of irrigation) can affect root water uptake but has does not significantly affect nitrate concentrations. It should also be emphasized that only drip-irrigated deciduous trees were simulated with the 3D model. Furthermore, the application of fertigation and the evaluation of the fate of nitrates in the soil were only performed in one study, in an apple orchard.

Table 4. Summary of HYDRUS 2D/3D simulations in deciduous trees.

Research Report	Crop	Soil Type	Irrigation System [1]	Irrigation Treatment [2]	HYDRUS 2D/3D	Simulation Processes
Yao et al. [81]	jujube	(soil depth 0–60): loam (soil depth 60–100): clay loam	DI-2 drip lines	-	2D	Water flow Root uptake
Phogat et al. [85]	almond	(homogenous soil depth 0–150): sand	DI-2 drip lines	Ip vs. Ic	2D	Water flow Root uptake Salinity dynamics
Phogat et al. [9]	almond	(homogenous soil depth 0–150): sand	DI-2 drip lines	Ip vs. Ic	2D	Water flow Root uptake Salinity dynamics
Phogat et al. [84]	almond	(homogenous soil depth 0–150): sand	DI-2 drip lines	FIp: 100% Etc SDIp: 65% Etc FIc: 100% Etc	2D	Water flow Root uptake Salinity dynamics

Table 4. *Cont.*

Research Report	Crop	Soil Type	Irrigation System [1]	Irrigation Treatment [2]	HYDRUS 2D/3D	Simulation Processes
Janssens et al. [87]	pear	(homogenous soil depth): silt loam	DI-1 drip line	SDI: 80% ETc SDI: 50% ETc	2D	Water flow Root uptake
Xi et al. [88]	*P. tomentosa* plantation	(soil depth 0–120): silt (soil depth >120): silt loam	SubDI-3 drip lines/tree belt	T25 No irrigation	2D 1D	Water flow Root uptake
Hardie et al. [93]	apple	(soil depth 0–30): sandy loam (soil depth 30–50): sandy loam (soil depth 50–70): light clay (soil depth >70): medium clay	DI-1 drip line and fertigation	low rate high rate	2D	Water flow Root uptake Nitrate dynamics
Yang et al. [86]	*P. tomentosa* plantation	(soil depth 0–140): sandy loam ((soil depth 140–300): silt loam	DI-2 drip lines	T20	2D	Water flow Root uptake
Domínguez-Niño et al. [82]	apple	(soil depth 0–60): loam	DI-1 drip line	FI: 100% ETc	3D	Water flow Root uptake
Domínguez-Niño et al. [83]	apple	(soil depth 0–60): loam	DI-1 drip line	FI: 100% ETc	3D	Water flow Root uptake
Nazari et al. [89]	apple	(soil depth 0–30): loam (soil depth 30–120): sandy loam	SubDI-2 drip lines	different discharge and duration	2D	Water flow Root uptake
Bughici et al. [92]	pistachio	(homogenous soil depth): clay loam	DI-1 drip line	high salinity low salinity	2D	Water flow Root uptake Salinity dynamics

Notes: [1] SubDI: Subsurface Drip Irrigation; DI: Drip Irrigation. [2] FI: Full Irrigation; RDI: Regular Deficit Irrigation; SDI: Sustained Deficit Irrigation; Ip: Pulsed Irrigation; Ic: Continuous Irrigation; Tn: a treatment in which the trees were irrigated when the average soil water potential at 20 cm depth from the dripper reached − n kPa.

7. Conclusions and Future Challenges

Reliable information on the wetted area of soil under drip irrigation helps researchers and farmers determine the optimal irrigation design (emitter flow, distances from the trunk, number of laterals, etc.) and optimal strategy/treatment (deficit or full irrigation, rate, frequency and timing of application) for effective use of water and fertilizer. Thus, there is a need for a simple and inexpensive yet robust calculation and visualization of water and solute transport patterns to support irrigation design and management. The HYDRUS 2D/3D model has proven to be able to predict soil water dynamics, root uptake and salinity/nitrate dynamics well to a good extent in orchards under surface or subsurface drip irrigation conditions.

Despite the widespread use of drip irrigation and fertigation systems in tree crops, there are relatively few studies that use the 2D/3D model HYDRUS to simulate water dynamics, root uptake and solute transport in drip-irrigated trees. Twenty-two papers were found in the literature, of which only three involve subsurface drip irrigation and the rest involve surface drip irrigation. The irrigation schemes in these studies consist of one two or more laterals per tree row, while only one study (conducted in a lysimeter) uses the scheme of a concentric dripline around the trunk. In addition, from the studies discussed in this paper, only four examine the fate of nitrate in the soil after fertilization and only two are based on field measurements of nitrate from the soil solution. An estimation of nitrate dynamics within and outside the plant root zone is necessary to fully assess the efficiency of irrigation systems. In addition, although there are studies on the effects of irrigation with wastewater, there is no study that considers the salinity dynamics in the soil. Therefore, there is a need for further research that will assess more irrigation schemes in the field and will investigate the fate of nitrates and the salinity distribution in soil under different tree crops, different tree crops, soil types and climatic conditions. Such studies would help improve irrigation and fertigation designs and strategies for perennial crops irrigated with drip irrigation systems and lead to more efficient and less environmentally damaging cropping practices.

Another challenge is the simulation under drip-irrigated trees in three-dimensional domains. To date, only two studies have attempted to simulate soil water dynamics under trees using HYDRUS 3D, with a particular focus on estimating soil hydraulic parameters. This means that there is a wide field for studies on simulating the three-dimensional movement of water, heat and solutes under different tree crops.

HYDRUS, like all the hydrological models, has shortcomings due to the simplification of surface and subsurface processes. Hydrological models require several input parameters which may not be available or may be of a large cost to acquire. Thus, in all the HYDRUS 2D/3D studies, many parameters had to be estimated either using optimization algorithms or during model calibration. Moreover, further improvements are needed in the accuracy and computational efficiency of the numerical solutions of the governing equations to facilitate larger-scale applications. There is a gap between physically based models at small spatial scales and landscape approaches. This is a significant challenge that needs to be overcome for HYDRUS models to be useful for decision makers.

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References

1. Provenzano, G.; Sinobas, L.R. Special issue on trends and challenges of sustainable irrigated agriculture. *J. Irrig. Drain. Eng.* **2014**, *140*, A2014001. [CrossRef]
2. FAO. FAOSTAT: Statistical Reports of Plant Production. 2021. Available online: http://www.fao.org/faostat/en/#data/QC (accessed on 27 January 2022).
3. Hamilton, A.J.; Stagnitti, F.; Xiong, X.; Kreidl, S.L.; Benke, K.K.; Maher, P. Wastewater irrigation: The state of play. *Vadose Zone J.* **2007**, *6*, 823–840. [CrossRef]
4. Assouline, S.; Narkis, K. Effects of long-term irrigation with treated wastewater on the root zone environment. *Vadose Zone J.* **2013**, *12*, 1–10. [CrossRef]
5. Morianou, G.; Ziogas, V.; Kourgialas, N.; Karatzas, G. Effect of irrigation practices upon yield and fruit quality of four grapefruit (*Citrus paradisi* Mac.) cultivars. *Water Supply* **2021**, *21*, 2735–2747. [CrossRef]

6. Gärdenäs, A.; Hopmans, J.; Hanson, B.; Šimůnek, J. Two-dimensional modeling of nitrate leaching for various fertigation scenarios under micro-irrigation. *Agric. Water Manag.* **2005**, *74*, 219–242. [CrossRef]
7. Dağdelen, N.; Başal, H.; Yılmaz, E.; Gürbüz, T.; Akcay, S. Different drip irrigation regimes affect cotton yield, water use efficiency and fiber quality in western Turkey. *Agric. Water Manag.* **2009**, *96*, 111–120. [CrossRef]
8. Subbaiah, R. A review of models for predicting soil water dynamics during trickle irrigation. *Irrig. Sci.* **2013**, *31*, 225–258. [CrossRef]
9. Phogat, V.; Mahadevan, M.; Skewes, M.; Cox, J.W. Modelling soil water and salt dynamics under pulsed and continuous surface drip irrigation of almond and implications of system design. *Irrig. Sci.* **2012**, *30*, 315–333. [CrossRef]
10. Kourgialas, N.N.; Koubouris, G.C.; Dokou, Z. Optimal irrigation planning for addressing current or future water scarcity in Mediterranean tree crops. *Sci. Total Environ.* **2019**, *654*, 616–632. [CrossRef]
11. Phogat, V.; Skewes, M.; Cox, J.; Alam, J.; Grigson, G.; Šimůnek, J. Evaluation of water movement and nitrate dynamics in a lysimeter planted with an orange tree. *Agric. Water Manag.* **2013**, *127*, 74–84. [CrossRef]
12. Arbat, G.; Puig-Bargués, J.; Duran-Ros, M.; Barragán, J.; de Cartagena, F.R. Drip-Irriwater: Computer software to simulate soil wetting patterns under surface drip irrigation. *Comput. Electron. Agric.* **2013**, *98*, 183–192. [CrossRef]
13. Communar, G.; Friedman, S.P. Relative water uptake rate as a criterion for trickle irrigation system design: I. Coupled source–sink steady water flow model. *Soil Sci. Soc. Am. J.* **2010**, *74*, 1493–1508. [CrossRef]
14. Cook, F.J.; Thorburn, P.J.; Fitch, P.; Bristow, K.L. WetUp: A software tool to display approximate wetting patterns from drippers. *Irrig. Sci.* **2003**, *22*, 129–134. [CrossRef]
15. Singh, D.; Rajput, T.; Sikarwar, H.; Sahoo, R.; Ahmad, T. Simulation of soil wetting pattern with subsurface drip irrigation from line source. *Agric. Water Manag.* **2006**, *83*, 130–134. [CrossRef]
16. van Dam, J.C.; Groenendijk, P.; Hendriks, R.F.A.; Kroes, J.G. Advances of modeling water flow in variably saturated soils with SWAP. *Vadose Zone J.* **2008**, *7*, 640–653. [CrossRef]
17. Šimůnek, J.; Van Genuchten, M.T.; Šejna, M. The HYDRUS software package for simulating two-and three-dimensional movement of water, heat, and multiple solutes in variably-saturated media. *Tech. Man. Version* **2006**, *1*, 241.
18. Šimůnek, J.; Van Genuchten, M.T.; Šejna, M. Recent developments and applications of the HYDRUS computer software packages. *Vadose Zone Journal* **2016**, *15*, 1–25. [CrossRef]
19. Cote, C.M.; Bristow, K.L.; Charlesworth, P.B.; Cook, F.J.; Thorburn, P.J. Analysis of soil wetting and solute transport in subsurface trickle irrigation. *Irrig. Sci.* **2003**, *22*, 143–156. [CrossRef]
20. Ben-Gal, A.; Lazorovitch, N.; Shani, U. Subsurface drip irrigation in gravel-filled cavities. *Vadose Zone J.* **2004**, *3*, 1407–1413. [CrossRef]
21. Kandelous, M.M.; Šimůnek, J. Comparison of numerical, analytical, and empirical models to estimate wetting patterns for surface and subsurface drip irrigation. *Irrig. Sci.* **2010**, *28*, 435–444. [CrossRef]
22. Autovino, D.; Rallo, G.; Provenzano, G. Predicting soil and plant water status dynamic in olive orchards under different irrigation systems with Hydrus-2D: Model performance and scenario analysis. *Agric. Water Manag.* **2018**, *203*, 225–235. [CrossRef]
23. Vrugt, J.; Hopmans, J.W.; Šimůnek, J. Calibration of a two-dimensional root water uptake model. *Soil Sci. Soc. Am. J.* **2001**, *65*, 1027–1037. [CrossRef]
24. Saitta, D.; Consoli, S.; Ferlito, F.; Torrisi, B.; Allegra, M.; Longo-Minnolo, G.; Ramírez-Cuesta, J.M.; Vanella, D. Adaptation of citrus orchards to deficit irrigation strategies. *Agric. Water Manag.* **2021**, *247*, 106734. [CrossRef]
25. De Silva, M.; Nachabe, M.; Šimůnek, J.; Carnahan, R. Simulating root water uptake from a heterogeneous vegetative cover. *J. Irrig. Drain. Eng.* **2008**, *134*, 167–174. [CrossRef]
26. Deb, S.K.; Shukla, M.K.; Šimůnek, J.; Mexal, J.G. Evaluation of spatial and temporal root water uptake patterns of a flood-irrigated pecan tree using the HYDRUS (2D/3D) model. *J. Irrig. Drain. Eng.* **2013**, *139*, 599–611. [CrossRef]
27. Han, M.; Zhao, C.; Feng, G.; Yan, Y.; Sheng, Y. Evaluating the effects of mulch and irrigation amount on soil water distribution and root zone water balance using HYDRUS-2D. *Water* **2015**, *7*, 2622–2640. [CrossRef]
28. Li, J.; Zhang, J.; Rao, M. Wetting patterns and nitrogen distributions as affected by fertigation strategies from a surface point source. *Agric. Water Manag.* **2004**, *67*, 89–104. [CrossRef]
29. Li, J.; Zhang, J.; Rao, M. Modeling of water flow and nitrate transport under surface drip fertigation. *Trans. ASAE* **2005**, *48*, 627–637. [CrossRef]
30. Hanson, B.R.; Šimůnek, J.; Hopmans, J.W. Evaluation of urea–ammonium–nitrate fertigation with drip irrigation using numerical modeling. *Agric. Water Manag.* **2006**, *86*, 102–113. [CrossRef]
31. Ajdary, K.; Singh, D.; Singh, A.K.; Khanna, M. Modelling of nitrogen leaching from experimental onion field under drip fertigation. *Agric. Water Manag.* **2007**, *89*, 15–28. [CrossRef]
32. Wehrhan, A.; Kasteel, R.; Simunek, J.; Groeneweg, J.; Vereecken, H. Transport of sulfadiazine in soil columns—Experiments and modelling approaches. *J. Contam. Hydrol.* **2007**, *89*, 107–135. [CrossRef]
33. Engelhardt, I.; Sittig, S.; Šimůnek, J.; Groeneweg, J.; Pütz, T.; Vereecken, H. Fate of the antibiotic sulfadiazine in natural soils: Experimental and numerical investigations. *J. Contam. Hydrol.* **2015**, *177*, 30–42. [CrossRef]
34. Karandish, F.; Šimůnek, J. A comparison of the HYDRUS (2D/3D) and SALTMED models to investigate the influence of various water-saving irrigation strategies on the maize water footprint. *Agric. Water Manag.* **2019**, *213*, 809–820. [CrossRef]

35. Karandish, F.; Šimůnek, J. Two-dimensional modeling of nitrogen and water dynamics for various N-managed water-saving irrigation strategies using HYDRUS. *Agric. Water Manag.* **2017**, *193*, 174–190. [CrossRef]
36. García Morillo, J.; Rodríguez Díaz, J.; Camacho, E.; Montesinos, P. Drip irrigation scheduling using HYDRUS 2-D numerical model application for strawberry production in South-West Spain. *Irrig. Drain.* **2017**, *66*, 797–807. [CrossRef]
37. Skaggs, T.; Trout, T.; Šimůnek, J.; Shouse, P. Comparison of HYDRUS-2D simulations of drip irrigation with experimental observations. *J. Irrig. Drain. Eng.* **2004**, *130*, 304–310. [CrossRef]
38. Sharmiladevi, R.; Ravikumar, V. Simulation of nitrogen fertigation schedule for drip irrigated paddy. *Agric. Water Manag.* **2021**, *252*, 106841. [CrossRef]
39. Arbat, G.; Cufí, S.; Duran-Ros, M.; Pinsach, J.; Puig-Bargués, J.; Pujol, J.; Ramírez de Cartagena, F. Modeling approaches for determining dripline depth and irrigation frequency of subsurface drip irrigated rice on different soil textures. *Water* **2020**, *12*, 1724. [CrossRef]
40. Grecco, K.L.; de Miranda, J.H.; Silveira, L.K.; van Genuchten, M.T. HYDRUS-2D simulations of water and potassium movement in drip irrigated tropical soil container cultivated with sugarcane. *Agric. Water Manag.* **2019**, *221*, 334–347. [CrossRef]
41. Azad, N.; Behmanesh, J.; Rezaverdinejad, V.; Abbasi, F.; Navabian, M. Developing an optimization model in drip fertigation management to consider environmental issues and supply plant requirements. *Agric. Water Manag.* **2018**, *208*, 344–356. [CrossRef]
42. Phogat, V.; Šimůnek, J.; Skewes, M.; Cox, J.; McCarthy, M. Improving the estimation of evaporation by the FAO-56 dual crop coefficient approach under subsurface drip irrigation. *Agric. Water Manag.* **2016**, *178*, 189–200. [CrossRef]
43. Ramos, T.; Šimůnek, J.; Gonçalves, M.; Martins, J.; Prazeres, A.; Pereira, L. Two-dimensional modeling of water and nitrogen fate from sweet sorghum irrigated with fresh and blended saline waters. *Agric. Water Manag.* **2012**, *111*, 87–104. [CrossRef]
44. Lazarovitch, N.; Warrick, A.; Furman, A.; Simunek, J. Subsurface water distribution from drip irrigation described by moment analyses. *Vadose Zone J.* **2007**, *6*, 116–123. [CrossRef]
45. Phogat, V.; Pitt, T.; Stevens, R.; Cox, J.; Šimůnek, J.; Petrie, P. Assessing the role of rainfall redirection techniques for arresting the land degradation under drip irrigated grapevines. *J. Hydrol.* **2020**, *587*, 125000. [CrossRef]
46. Williams, C.A.; Albertson, J.D. Soil moisture controls on canopy-scale water and carbon fluxes in an African savanna. *Water Resour. Res.* **2004**, *40*, 9. [CrossRef]
47. Kandelous, M.M.; Šimůnek, J. Numerical simulations of water movement in a subsurface drip irrigation system under field and laboratory conditions using HYDRUS-2D. *Agric. Water Manag.* **2010**, *97*, 1070–1076. [CrossRef]
48. Šimůnek, J.; van Genuchten, M.T.; Šejna, M. *The HYDRUS Software Package for Simulating Two- and Three-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Porous Media*; Technical Manual, Version 3.0; PC Progress: Prague, Czech Republic, 2018; Volume 274.
49. Feddes, R.A.; Kowalik, P.J.; Zaradny, H. Simulation of Field Water Use and Crop Yield. In *Simulation of Plant Growth and Crop Production*; Pudoc: Wageningen, The Netherlands, 1978.
50. Mualem, Y. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resour. Res.* **1976**, *12*, 513–522. [CrossRef]
51. Van Genuchten, M.T. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* **1980**, *44*, 892–898. [CrossRef]
52. Lu, P.; Zhang, Z.; Sheng, Z.; Huang, M.; Zhang, Z. Assess effectiveness of salt removal by a subsurface drainage with bundled crop straws in coastal saline soil using HYDRUS-3D. *Water* **2019**, *11*, 943. [CrossRef]
53. Ziogas, V.; Tanou, G.; Morianou, G.; Kourgialas, N. Drought and salinity in citriculture: Optimal practices to alleviate salinity and water stress. *Agronomy* **2021**, *11*, 1283. [CrossRef]
54. Kourgialas, N.N.; Karatzas, G.P. A modeling approach for agricultural water management in citrus orchards: Cost-effective irrigation scheduling and agrochemical transport simulation. *Environ. Monit. Assess.* **2015**, *187*, 1–21. [CrossRef]
55. Panigrahi, P.; Sharma, R.K. Using hydrus-2D model for simulating soil water dynamics in drip-irrigated citrus. *Agric. Eng.* **2016**, *1*, 59–68.
56. Legates, D.R.; McCabe, G.J., Jr. Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resour. Res.* **1999**, *35*, 233–241. [CrossRef]
57. Phogat, V.; Skewes, M.; Cox, J.; Sanderson, G.; Alam, J.; Šimůnek, J. Seasonal simulation of water, salinity and nitrate dynamics under drip irrigated mandarin (*Citrus reticulata*) and assessing management options for drainage and nitrate leaching. *J. Hydrol.* **2014**, *513*, 504–516. [CrossRef]
58. Phogat, V.; Skewes, M.; Cox, J.; Simunek, J. Statistical assessment of a numerical model simulating agro hydro-chemical processes in soil under drip fertigated mandarin tree. *Irrig. Drain. Syst. Eng.* **2016**, *5*, 1–9.
59. Tejero, I.G.; Zuazo, V.H.D.; Bocanegra, J.A.J.; Fernández, J.L.M. Improved water-use efficiency by deficit-irrigation programmes: Implications for saving water in citrus orchards. *Sci. Hortic.* **2011**, *128*, 274–282. [CrossRef]
60. Doorenbos, J.; Kassam, A.H. Yield response to water. *FAO Irrig. Drain. Pap.* **1979**, *33*, 257.
61. Castel, J.R.; Buj, A. Response of Salustiana orange to high frequency deficit irrigation. *Irrig. Sci.* **1990**, *11*, 121–127. [CrossRef]
62. Pérez-Pérez, J.G.; Romero, P.; Navarro, J.M.; Botía, P. Response of sweet orange cv 'Lane late'to deficit irrigation in two rootstocks. I: Water relations, leaf gas exchange and vegetative growth. *Irrig. Sci.* **2008**, *26*, 415–425. [CrossRef]
63. González-Altozano, P.; Castel, J.R. Regulated deficit irrigation in 'Clementina de Nules' citrus trees. I. Yield and fruit quality effects. *J. Hortic. Sci. Biotech.* **1999**, *74*, 706–713. [CrossRef]

64. González-Altozano, P.; Castel, J.R. Regulated deficit irrigation in 'Clementina de Nules' citrus trees. II: Vegetative growth. *J. Hortic. Sci. Biotech.* **2000**, *75*, 388–392. [CrossRef]
65. González-Altozano, P.; Castel, J.R. Riego deficitario controlado en 'Clementina de Nules'. I. Efectos sobre la producciónyla calidad de la fruta. *Span. J. Agric. Res.* **2003**, *1*, 81–92.
66. García-Tejera, O.; López-Bernal, Á.; Orgaz, F.; Testi, L.; Villalobos, F.J. Are olive root systems optimal for deficit irrigation? *Eur. J. Agron.* **2018**, *99*, 72–79. [CrossRef]
67. Egea, G.; Diaz-Espejo, A.; Fernández, J.E. Soil moisture dynamics in a hedgerow olive orchard under well-watered and deficit irrigation regimes: Assessment, prediction and scenario analysis. *Agric. Water Manag.* **2016**, *164*, 197–211. [CrossRef]
68. Fernandes, R.D.; Egea, G.; Hernandez-Santana, V.; Diaz-Espejo, A.; Fernández, J.; Perez-Martin, A.; Cuevas, M. Response of vegetative and fruit growth to the soil volume wetted by irrigation in a super-high-density olive orchard. *Agric. Water Manag.* **2021**, *258*, 107197. [CrossRef]
69. Carlos, F.U.; Cristian, K.F.; Marco, G.S.; Mauricio, G.; Humberto, A.; de Miranda Jarbas, H.; Oscar, S.S. Testing the Model Efficiency of HYDRUS 2D/3D Under Desert Conditions for Water Content and Pore Electrical Conductivity: A Case Study in an Olive Orchard. *J. Soil Sci. Plant Nutr.* **2022**, *22*, 1859–1872. [CrossRef]
70. CBI. The European Market Potential for Avocados. 2021. Available online: https://www.cbi.eu/market-information/fresh-fruitvegetables/avocados/market-entry (accessed on 25 July 2022).
71. Schaffer, B.A.; Wolstenholme, B.N.; Whiley, A.W. *The Avocado: Botany, Production and Uses*; CABI: Wallingford, UK, 2013.
72. Tzatzani, T.-T.; Kavroulakis, N.; Doupis, G.; Psarras, G.; Papadakis, I.E. Nutritional status of 'Hass' and 'Fuerte' avocado (Persea americana Mill.) plants subjected to high soil moisture. *J. Plant Nutr.* **2020**, *43*, 327–334. [CrossRef]
73. Tzatzani, T.-T.; Psarras, G.; Scuderi, D.; Kokolakis, E.; Papadakis, I.E. Effect of Organic Fertilizers on Avocado Trees (Cvs. Fuerte, Hass, Lamb Hass) in Western Crete, a Cool Subtropical Region. *Sustainability* **2022**, *14*, 12221. [CrossRef]
74. Kourgialas, N.N.; Dokou, Z. Water management and salinity adaptation approaches of Avocado trees: A review for hot-summer Mediterranean climate. *Agric. Water Manag.* **2021**, *252*, 106923. [CrossRef]
75. Assouline, S.; Narkis, K. Effects of long-term irrigation with treated wastewater on the hydraulic properties of a clayey soil. *Water Resour. Res.* **2011**, *47*, 8. [CrossRef]
76. Assouline, S.; Kamai, T.; Šimůnek, J.; Narkis, K.; Silber, A. Mitigating the impact of irrigation with effluent water: Mixing with freshwater and/or adjusting irrigation management and design. *Water Resour. Res.* **2020**, *56*, e2020WR027781. [CrossRef]
77. Hassena, A.B.; Zouari, M.; Trabelsi, L.; Khabou, W.; Zouari, N. Physiological improvements of young olive tree (Olea europaea L. cv. Chetoui) under short term irrigation with treated wastewater. *Agric. Water Manag.* **2018**, *207*, 53–58. [CrossRef]
78. Luedeling, E.; Brown, P.H. A global analysis of the comparability of winter chill models for fruit and nut trees. *Int. J. Biometeorol.* **2011**, *55*, 411–421. [CrossRef]
79. Uriu, K.; Magness, J. Deciduous tree fruits and nuts. *Irrig. Agric. Lands* **1967**, *11*, 686–703.
80. Browne, G.T.; Beede, R.H.; Schmidt, L.S. Irrigation water and the health of deciduous fruit and nut crops. In *Biology, Detection, and Management of Plant Pathogens in Irrigation Water*; Hong, C., Moorman, G., Eds.; APS Press: St. Paul, MN, USA, 2012; pp. 43–53.
81. Yao, P.; Dong, X.; Hu, A. Using HYDRUS-2D simulate soil water dynamic in jujube root zone under drip irrigation. In Proceedings of the 2011 International Symposium on Water Resource and Environmental Protection, Xi'an, China, 20–22 May 2011; pp. 684–688.
82. Domínguez-Niño, J.M.; Oliver-Manera, J.; Arbat, G.; Girona, J.; Casadesús, J. Analysis of the Variability in Soil Moisture Measurements by Capacitance Sensors in a Drip-Irrigated Orchard. *Sensors* **2020**, *20*, 5100. [CrossRef]
83. Domínguez-Niño, J.M.; Arbat, G.; Raij-Hoffman, I.; Kisekka, I.; Girona, J.; Casadesús, J. Parameterization of soil hydraulic parameters for HYDRUS-3D simulation of soil water dynamics in a drip-irrigated orchard. *Water* **2020**, *12*, 1858. [CrossRef]
84. Phogat, V.; Skewes, M.A.; Mahadevan, M.; Cox, J. Evaluation of soil plant system response to pulsed drip irrigation of an almond tree under sustained stress conditions. *Agric. Water Manag.* **2013**, *118*, 1–11. [CrossRef]
85. Phogat, V.; Skewes, M.; Cox, J.; Mahadevan, M. Modelling the impact of pulsing of drip irrigation on the water and salinity dynamics in soil in relation to water uptake by an almond tree. *WIT Trans. Ecol. Environ.* **2012**, *168*, 101–113.
86. Yang, T.; Li, D.; Clothier, B.; Wang, Y.; Duan, J.; Di, N.; Li, G.; Li, X.; Jia, L.; Xi, B. Where to monitor the soil-water potential for scheduling drip irrigation in Populus tomentosa plantations located on the North China Plain? *For. Ecol. Manag.* **2019**, *437*, 99–112. [CrossRef]
87. Janssens, P.; Diels, J.; Vanderborght, J.; Elsen, F.; Elsen, A.; Deckers, T.; Vandendriessche, H. Numerical calculation of soil water potential in an irrigated 'conference' pear orchard. *Agric. Water Manag.* **2015**, *148*, 113–122. [CrossRef]
88. Xi, B.; Bloomberg, M.; Watt, M.S.; Wang, Y.; Jia, L. Modeling growth response to soil water availability simulated by HYDRUS for a mature triploid Populus tomentosa plantation located on the North China Plain. *Agric. Water Manag.* **2016**, *176*, 243–254. [CrossRef]
89. Nazari, E.; Besharat, S.; Zeinalzadeh, K.; Mohammadi, A. Measurement and simulation of the water flow and root uptake in soil under subsurface drip irrigation of apple tree. *Agric. Water Manag.* **2021**, *255*, 106972. [CrossRef]
90. Elmaloglou, S.; Diamantopoulos, E. Simulation of soil water dynamics under subsurface drip irrigation from line sources. *Agric. Water Manag.* **2009**, *96*, 1587–1595. [CrossRef]
91. Mohammad, N.; Alazba, A.; Šimůnek, J. HYDRUS simulations of the effects of dual-drip subsurface irrigation and a physical barrier on water movement and solute transport in soils. *Irrig. Sci.* **2014**, *32*, 111–125.

92. Bughici, T.; Skaggs, T.H.; Corwin, D.L.; Scudiero, E. Ensemble HYDRUS-2D modeling to improve apparent electrical conductivity sensing of soil salinity under drip irrigation. *Agric. Water Manag.* **2022**, *272*, 107813. [CrossRef]
93. Hardie, M.; Ridges, J.; Swarts, N.; Close, D. Drip irrigation wetting patterns and nitrate distribution: Comparison between electrical resistivity (ERI), dye tracer, and 2D soil–water modelling approaches. *Irrig. Sci.* **2018**, *36*, 97–110. [CrossRef]