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Developing an optimization model in drip fertigation management to consider environmental issues and supply plant requirements

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ABSTRACT

Recently, groundwater contamination has increased due to incorrect use of nitrogen fertilizers so that it has caused public concern. To solve the problem, the most appropriate approach is to manage on-time and correct application of water and fertilizer. The objective of this study was to provide an optimization program of drip irrigation and fertigation to maximize the nutrients uptake by plants and minimize water and solute losses in field by optimizing the design and management parameters of drip fertigation. In this research, the HYDRUS (2D/3D) model was used to simulate water and nitrogen transport in soil. For this purpose, the requirement data for calibration and validation of the model were collected by carrying out corn field experiments and performing drip irrigation and fertigation. Then, the calibrated model was used to simulate water and nitrogen behavior in soil and optimization process. To optimize the design and management parameters of fertigation, a two-stage optimization program was considered. In the first stage, the amount of irrigation flow rate, duration of fertilizer injection, and the start time of the injection were simultaneously optimized with the aim of minimizing nitrate leaching in a fertigation cycle. The results showed that by selecting the irrigation rate of 0.8 L h^{-1} and minimum duration of fertigation at the end of irrigation, nitrate leaching was minimum in the period of fertigation. In the second stage, the amount of fertilizer injection at each stage of fertigation was optimized throughout the growth season using the optimum values of the previous step. In fact, in addition to supplying nitrogen requirement of the plant, the amount of nitrate leaching and its accumulation at the end of each fertigation, especially at the end of the growing season, were also minimized to prevent leaching by post-harvest rainfall.

1. Introduction

In recent years, population growth and the need for producing more food have led to an increase in the use of chemical fertilizers in agriculture. However, due to the lack of proper management in water and fertilizer consumption, soil nutrient balance has been disturbed and many environmental problems have arisen. Nitrogen is a necessary nutrient for plants, and nitrate- a very mobile and leachable element- is one of the most important forms of nitrogen found in soil (Alva et al., 2008). Studies have indicated that nitrate is the most common and widespread contaminant of groundwater in the world and can lead to health problems (Marinov and Marinov, 2014).

Best management practices that reduce the amount of water and nitrogen influx without decreasing the yield can decline the potential of nitrate pollution of groundwater (Shrestha et al., 2010). This management should consider different soil moisture management strategies for nitrate transport and managing the application of nitrogen (amount and time) by considering the plant requirement for nitrogen (Shrestha et al., 2010). Inappropriate irrigation management causes water and nutrient losses from the root zone and, as a result, contaminates groundwater. Therefore, optimal irrigation planning is important in improving the water and nutrient uptake efficiency (Alva et al., 2006). Overuse of fertilizers is another reason for nitrogen leaching. With an increase in nitrogen application, nitrate leaching rapidly increases (Zvomuya et al., 2003). Recent studies have emphasized that there is a positive correlation between the groundwater nitrate and the intensity of nitrate application in agriculture (Costa et al., 2002). For example, West Bengal's villages have recorded high concentration of nitrate in their underground water because of using high levels of nitrogen fertilizer (Kundu and Mandal, 2009). On the other hand, split application of fertilizer can play an important role in improving fertilizer uptake by plants and reduce fertilizer leaching and environmental

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contaminations. Some studies have reported the reduction in nitrate leaching and increase in yield with nitrogen split in sandy loam soils (Errebhi et al., 1998; Waddell et al., 2000). Silber et al. (2003) showed that high fertigation frequency causes significant increase in performance, mostly in low levels of nutrient concentration which is due to the increase in nutrient absorption. In addition, it is necessary to apply nitrogen fertilizer at the correct time and coordinate the time of fertigation and plant requirement (Zebarth and Rosen, 2007).

It can be concluded that proper management of all effective factors in the water and solute transport in the soil is important to increase the efficiency of fertilizer usage and reduce its losses. Several researchers around the world have recognized the importance of this issue, and various studies have been conducted to investigate the effects of various fertigation strategies on the movement and distribution of nitrogen in the soil. Some of these studies have been carried out in a short run and often in one irrigation cycle (Li et al., 2003, 2004). Some other long-term and seasonal studies have examined the impact of various fertigation strategies on the distribution of nitrate in the soil including different levels of water and fertilizer, irrigation and fertigation intervals and injection times and concentration (Hou et al., 2009; Kumar et al., 2016). Rajput and Patel (2006) in investigating the impact of different fertigation intervals (daily, alternate, weekly and monthly) on nitrate movement in the soil showed that a large amount of nitrate was leached in monthly fertigation. In another study, the nitrate leaching in the corn farm was investigated by Gheysari et al. (2009) in different rates of irrigation and nitrogen fertilization levels. Farneselli et al. (2015) showed that the high frequency of fertigation and/or irrigation could be a strategy to increase the nitrogen uptake efficiency in tomato fed with very high N and water supply (which often exists in tomato production).

In recent decades, many models have been developed for simulating water flow and solute transfer in soil. These models are able to study different strategies by calibrating the simulation model rather than conducting various time-consuming and costly field experiments. Simulation models are now recognized as an important tool for optimized planning of agricultural systems and have a significant and increasing role in modern methods of water resources conservation and sustainable agricultural production (Šimůnek and Bradford, 2008). One of the most advanced and widely used software packages is HYDRUS-1D and HYDRUS (2D/3D) (Šimůnek et al., 2011) which has the ability to simulate water and solute transport in soil by determining root distribution and water and nutrient uptake by the plant. This model has been used to simulate the application of fertigation and the process of nitrogen species transport and different fertigation strategies in different researches. Some of the researches include short-term simulations in the laboratory without the plants (Li et al., 2005; Zeng et al., 2013; Zhang et al., 2015). Despite the importance of these researches in the early understanding of water and solute movement in the soil, new studies have also been carried out in investigating different fertigation strategies with the plant due to the effect of the plant on the absorption of solutes and its movement in soil (Phogat et al., 2013, 2014; Ravikumar et al., 2011; Wang et al., 2014). Gardenas et al. (2005) investigated the effect of fertigation strategy and soil type on nitrate leaching potential for four different micro-irrigation systems (each associated with a typical crop) and showed that fertigation at the end of irrigation cycle decreased nitrate leaching. Hanson et al. (2006) following the previous work of Gardenas et al. (2005), modeled the distribution of soil nitrogen and nitrate leaching by considering various nutrient injection durations, injection times and concentrations. Ajdary et al. (2007) showed that nitrogen leaching can be minimized in shallow root crops by appropriate selection of emitter discharge, irrigation duration and its frequency. Also, in order to supply sugarcane requirement for nitrogen, the amounts of nitrogen fertilizer application were scheduled by Ravikumar et al. (2011) using trial and error method and simulation in HYDRUS. Ramos et al. (2012) in modeling water and nitrogen transport using HYDRUS-2D indicated that nitrogen movement outside the root zone depends on the amount of water flow and applied nitrogen, nitrogen form in fertilizer, its application time and number of fertigation events. According to the results of their study, high nitrate uptake occurred when the number of fertigation events was higher and the used amount was lower in each event. In another study, Karandish and Šimůnek (2017) evaluated the effects of different strategies (including 11 irrigation levels and 8 nitrogen fertilization rates in two partial root-zone drying and deficit irrigation scenarios) on the water and nitrogen movement and the yield of corn.

In the researches discussed above, fertigation strategies were compared in some limited scenarios in one irrigation event or in growth season using the experiment or a simulation model and the best scenario was selected. Despite the use of simulation models in determining the best fertigation strategies, optimization methods along with simulation models can be useful tools in optimal managing of irrigation and fertigation. In fact, using an optimization algorithm, a wide range of several design and management parameters can be simultaneously investigated and the best combination of parameters can be selected. In the use of optimization tools along with simulation models for proper fertigation planning, only a few studies in surface irrigation have been conducted to optimize the design and management parameters of furrow irrigation in an irrigation event. Ebrahimian et al. (2013) and Ebrahimian and Playán (2014) designed an alternative and conventional furrow fertigation to optimally reduce nitrate losses. They used the genetic algorithm and included inflow discharge, irrigation cutoff and start times and duration of fertilizer injection as optimizing decision variables to maximize the two objective functions of water and nitrate application efficiency plus uniformity.

Due to the high nitrate leaching potential, inappropriate scheduling of fertilizer application not only causes its losses during the growing season, but its accumulation at the end of the growing season in the soil profile has the potential for leaching and groundwater contamination by autumn rainfall after crop harvesting. Therefore, optimization of the fertigation parameters based on the decreasing nitrate leaching in one event is not sufficient, and proper application of fertigation during the growing season should be simultaneously considered. Optimum application of nutrients in the crop root zone ensures their optimum utilization, higher crop yield and lesser nutrients losses. Thus, optimization of fertigation has an important role in implementation of micro-irrigation systems to gain better quality and quantity of agricultural productions without degradation of soil and groundwater. The main objective of this study is to present a process to optimize the design and management parameters of drip fertigation. So that, the goals of this optimization include supplying corn requirement to nitrogen, reducing the contaminant of nitrate leaching in the fertigation process and avoiding nitrogen accumulation in the soil at the end of growth season. In fact, using the results of this research, a comprehensive plan for fertigation design and management and in different conditions of soil, plant, climate and irrigation system can be presented and applied.

2. Materials and methods

2.1. Field study

In the present research, field experiments were conducted in the study area of Urmia University (37° 39′ N, 44° 58′ E, and 1362 m above the sea level). Urmia University was located in Urmia plain. The coldest month in this plain is January with normal minimum temperature of −15.1 °C and the warmest month is July with normal maximum temperature of 35.5 °C. The normal annual precipitation is 340 mm. The data for calibration and validation phases was collected for modeling process. For this purpose, corn (Maxima variety) was planted on June 24, 2016 in a rectangular farm with dimensions of 20 m × 30 m. Planting rows distance and plants space in a row were 75 and 30 cm respectively. To achieve the soil physical properties, soil samples were obtained from 5 layers up to a depth of 90 cm (0–10, 10–30, 30–50,