Journal of Environmental Management 213 (2018) 341–352

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Exploring the effects of nitrogen fertilization management alternatives on nitrate loss and crop yields in tile-drained fields in Illinois

Hanseok Jeong, Rabin Bhattarai*

Department of Agricultural and Biological Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

ARTICLE INFO

Article history:
Received 14 July 2017
Received in revised form
9 February 2018
Accepted 15 February 2018

Keywords:
Best management practices
DSSAT
Maximum return to nitrogen
Nitrate loss
RZWQM
Tile flow

ABSTRACT

It is vital to manage the excessive use of nitrogen (N) fertilizer in corn production, the single largest consumer of N fertilizer in the United States, in order to achieve more sustainable agroecosystems. This study comprehensively explored the effects of N fertilization alternatives on nitrate loss and crop yields using the Root Zone Water Quality Model (RZWQM) in tile-drained fields in central Illinois. The RZWQM was tested for the prediction of tile flow, nitrate loss, and crop yields using eight years (1993–2000) of observed data and showed satisfactory model performances from statistical and graphical evaluations. Our model simulations demonstrated the maximum return to nitrogen (MRTN) rate (193 $kg\ ha^{-1}$), a newly advised N recommendation by the Illinois Nutrient Loss Reduction Strategy (INLRS), can be further reduced. Nitrate loss was reduced by 10.3% and 29.8%, but corn yields decreased by 0.3% and 1.9% at 156 and 150 $kg\ ha^{-1}$ of N fertilizer rate in the study sites A and E, respectively. Although adjustment of N fertilization timing presented a further reduction in nitrate loss, there was no optimal timing to ensure nitrate loss reduction and corn productivity. For site A, 100% spring application was the most productive and 40% fall, 10% pre-plant, and 50% side dress application generated the lowest nitrate loss. For site E, the conventional N application timing was verified as the best practice in both corn production and nitrate loss reduction. Compared to surface broadcast placement, injected N fertilizer in spring increased corn yield, but may also escalate nitrate loss. This study presented the need of an adaptive N fertilizer management due to the heterogeneity in agricultural systems, and raised the importance of timing and placement of N fertilizer, as well as further reduction in fertilizer rate to devise a better in-field N management practice.

1. Introduction

Fertilizer has helped increase world crop productivity ahead of population growth (Vitousek et al., 2009). However, environmental costs from using fertilizer have been considerable (Buda et al., 2015). Corn is the largest consumer of nitrogen (N) fertilizer in the United States (Pimentel and Patzek, 2005). The state of Illinois alone plants more than 4.4 million ha and produces about 57.3 million tons of corn each year, which accounts for approximately 5.4% of corn production worldwide (USDA, 2017a, 2017b). Agricultural runoff from land reserved for corn production is a significant source of nitrate loading into Illinois waterbodies and the Mississippi River Basin resulting in hypoxia in the Gulf of Mexico (David et al., 2010). The greatest nitrate loss in Illinois was found in tile drainage (Kalita et al., 2006). As a result, nitrate loss to tile drains is one of the main environmental concerns and managing the excessive use of N fertilizer in corn production can mitigate degradation of downstream water quality and eutrophication of aquatic ecosystems (e.g. Gulf of Mexico hypoxia) (Dinnes et al., 2002; Kröger et al., 2015).

Best management practices (BMPs) and strategies for fertilizer applications have been proposed to relieve water quality degradation (Dinnes et al., 2002; Ju et al., 2009; Robertson and Vitousek, 2009). There are many studies to assess the effects of N fertilizer applications on nitrate loss and crop yields in tile-drained landscapes for a better N management in agriculture (He et al., 2012; Nangia et al., 2008; Scharf et al., 2005). Motivated by the previous strategies and studies, the Illinois Nutrient Loss Reduction

* Corresponding author.
E-mail address: rbhatta2@illinois.edu (R. Bhattarai).

https://doi.org/10.1016/j.jenvman.2018.02.062
0301-4797/

Strategy (INLRS) newly included N fertilization alternatives, which suggested reducing fertilizer application rate to the maximum return to nitrogen (MRTN) rate and three alternative application timings, to diminish nitrate loss (IEPA and IDOA, 2015). The MRTN rate is, however, designed to only provide the most economical corn N recommendations (Sawyer et al., 2006), does not consider its environmental impacts. Furthermore, the newly advised N fertilizer alternatives of the INLRS have not been sufficiently assessed when it comes to their effects on both agricultural productivity and water quality. Therefore, this study aims to explore the effects of the N fertilizer alternatives on agricultural systems in tile-drained fields. By doing so, we can provide a robust evidence for devising a better in-field N management practice to the strategy for accelerating progress towards nutrient loading reduction goals.

Agricultural systems models can be a useful tool to investigate new knowledge gaps such as evaluating the effects of emerging agricultural practices (e.g. INLRS) on N dynamics and crop growth (Ma et al., 2007a). For example, the Agricultural Production Systems Simulator (APSIM) was used for simulating corn and soybean yields and the economic optimum N rate in central Iowa (Puntel et al., 2016). Some advanced versions of DRAINMOD have also been used for the simulation of N losses and crop yields in tile-drained fields across the Midwest (Ale et al., 2012; Liang et al., 2018; Negm et al., 2017). In this study, we used the Root Zone Water Quality Model (RZWQM) which has been widely used for tile-drained agroecosystems in the Midwest (Fang et al., 2012; Malone et al., 2007; Singer et al., 2011). The RZWQM, which is coupled with the Decision Support System for Agrotechnology Transfer (DSSAT), can evaluate most aspects of N fertilizer applications including rate, timing, and placement on agricultural systems pertaining to soil-water-plant relations (Qi et al., 2012).

Studies on N fertilizer managements using the RZWQM have been mainly focused on evaluating the effects of fertilizer rates and timings on agricultural systems (Ma et al., 2008; Saseendran et al., 2007). Thorp et al. (2007) simulated effects of N fertilizer application rates on corn yield and N loss and showed reducing N rates from 180 to 130 kg ha^{-1} yielded an 18% reduction in nitrate loss while maintaining acceptable corn production. Malone et al. (2007) tested the model in quantifying long-term N management effects by using several scenarios consisting of different N sources, rates, and timings. Although more emphasis has been placed on the timing and placement of N fertilizer in N management strategies (Robertson and Vitousek, 2009), comprehensive studies covering the fertilizer placement and three timings proposed by the INLRS have not been performed yet using the RZWQM.

Right fertilizer source at the right rate, at the right time, in the right place, which is referred as the 4Rs Nutrient Stewardship (Bruulsema et al., 2009), can be the principal of N management strategy. Many studies support the importance of the stewardship in increasing productivity and profitability (Chen et al., 2011; Xu et al., 2014), enhancing environmental protection and sustainability (Randall and Vetsch, 2005b). Our study tackles this stewardship particularly focusing on the rate, time, and place using the RZWQM in order to further explore N fertilization alternatives beyond the INLRS' in-field N managements, which only include the rate and time. Our modeling study proceeds as follows. First, we calibrate and validate RZWQM with a long-term (1993–2000) monitored data of tile flow, nitrate loss, and crop yields in tile-drained fields in Illinois. Second, using the validated RZWQM, we simulate the responses of agricultural systems, nitrate loss and crop yields, to the conventional N applications implemented in study fields and to the N fertilization alternatives including the MRTN rate and the three timings proposed by the INLRS. Third, we further explore the effects of N fertilizer placement, surface broadcast and injection, on tile-drained agroecosystems.

2. Materials and methods

2.1. Site description

The study sites were located in the Little Vermilion River watershed in east central Illinois, USA (Figure S1). The watershed shows typical plains characteristics of flat topography, poorly drained soils, and little surface runoff (Mitchell et al., 2000). Although several sites were established for a long-term water quality monitoring project (Mitchell et al., 2000; Kalita et al., 2006), monitoring results in a corn-soybean rotation from sites A and E between 1993 and 2000 were used for this study. For both sites, the landowners made their decisions about crop and fertilizer management practices, and information on tillage practices and fertilizer applications was collected (Table S1) (Kalita et al., 2006). Also, there was no irrigation practice in both sites. Site A, predominantly characterized by Drummer silty clay loam soil, was chisel plowed and disked or field cultivated each year and most of N was applied prior to planting corn (Mitchell et al., 2000). Site E, predominantly characterized by Sabina silt loam soil, was cultivated under a no-till system. For this site, N was applied in the spring once before planting and later side dress applications during the growing season (Mitchell et al., 2000).

Tile drainage of the two sites was continuously monitored at each tile drainage system outlet using Palmer-Bowlus flumes and data loggers that recorded time-stage data by increments of stage from stage recorders with potentiometers (Mitchell et al., 2000). For the site A, an area of 4.9 ha was drained with an irregularly spaced tile drainage system. For the site E, an area of 7.5 ha was drained with a complete drainage system at 28 m spacing (Mitchell et al., 2000). All of the tiles were placed at 1 to 1.5 m depth. Water samples were taken automatically by water samplers activated by the data logger when the tile was flowing. Additional water samples were collected at least biweekly (Mitchell et al., 2000). The water samples were analyzed for nitrate with the hydrazine sulfate reduction method (USEPA, 1978). Nitrate loss was computed by using volumes of tile flow and measured concentrations of nitrate in the flow (Kalita et al., 2006).

2.2. Model description

RZWQM is a field-scale agricultural system model to understand effects of agricultural management practices on water quantity, water quality, and crop response (Ma et al., 2012). RZWQM consists of six subsystems which represent physical, soil chemical, nutrient, pesticide, plant growth, and management processes (Ahuja et al., 2000). The model can predict hydrological processes, the fate of nutrients and pesticides, and crop growth with varying soils, climates, and management conditions over long periods of time. Since the RZWQM was first introduced in 1992, the model has been continuously improved to better represent the physical, chemical, and biological processes that govern the dynamics of the soil-plant-atmosphere system (Ahuja et al., 2000; Ma et al., 2012). The DSSAT crop growth model was also incorporated to better describe detailed crop growth and nutrient uptake (Ma et al., 2005). In this study, the RZWQM-DSSAT hybrid model, widely used and verified in the U.S. and the world (Fang et al., 2010; Saseendran et al., 2007; Yu et al., 2006), was applied. More detailed descriptions of the RZWQM, particularly for the model structures, can be found in Ahuja et al. (2000) and Thorp et al. (2007).

2.3. Model setup

The model requires data for soil, weather, and crop management. Physical and hydraulic properties data for Drummer and