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Effects of tillage and application rate on atrazine transport to subsurface drainage: Evaluation of RZWQM using a six-year field study

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ABSTRACT

Well tested agricultural system models can improve our understanding of the water quality effects of management practices under different conditions. The Root Zone Water Quality Model (RZWQM) has been tested under a variety of conditions. However, the current model's ability to simulate pesticide transport to subsurface drain flow over a long term period under different tillage systems and application rates is not clear. Therefore, we calibrated and tested RZWQM using six years of data from Nashua, Iowa. In this experiment, atrazine was spring applied at 2.8 (1990–1992) and 0.6 kg/ha/yr (1993–1995) to two 0.4 ha plots with different tillage (till and no-till). The observed and simulated average annual flow weighted atrazine concentrations (FWAC) in subsurface drain flow from the no-till plot were 3.7 and 3.2 μg/L, respectively for the period with high atrazine application rates, and 0.8 and 0.9 μg/L, respectively for the period with low application rates. The 1990–1992 observed average annual FWAC difference between the no-till and tilled plot was 2.4 μg/L while the simulated difference was 2.1 μg/L. These observed and simulated differences for 1993–1995 were 0.1 and 0.1 μg/L, respectively. The Nash–Sutcliffe model performance statistic (EF) for cumulative atrazine flux to subsurface drain flow was 0.93 for the no-till plot testing years (1993–1995), which is comparable to other recent model tests. The value of EF is 1.0 when simulated data perfectly match observed data. The order of selected parameter sensitivity for RZWQM simulated FWAC was atrazine partition coefficient > number of macropores > atrazine half life in soil > soil hydraulic conductivity. Simulations from 1990 to 1995 with four different atrazine application rates applied at a constant rate throughout the simulation period showed concentrations in drain flow for the no-till plot to be twice those of the tilled plot. The differences were more pronounced in the early simulation period (1990–1992), partly because of the characteristics of macropore flow during large storms. The results suggest that RZWQM is a promising tool to study pesticide transport to subsurface drain flow under different tillage systems and application rates over several years, the concentrations of atrazine in drain flow can be higher with no-till than tilled soil over a range of atrazine application rates, and atrazine concentrations in drain flow are sensitive to the macropore flow characteristics under different tillage systems and rainfall timing and intensity.

1. Introduction

After the first ten years of the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program (1992–2001), Gilliom et al. (2006) concluded that predictive modeling is critical for the successful assessment of U.S. water quality because the expense of direct monitoring prevents the acquisition of data at spatial and temporal resolutions required to manage water resources in a cost effective manner. Therefore, the current NAWQA Program heavily emphasizes the use of thoroughly tested models as a complement to monitoring. As part of this emphasis, one of the current goals of the NAWQA Program is to develop well tested models to predict pesticide transport from the land surface to the water table. Statistical models for pesticides in ground and surface water have been developed within the NAWQA Program (e.g., Stackelberg et al., 2012; Larson and Gilliom, 2001). However, the use of process based models for long-term prediction of pesticide fate and transport under subsurface drainage, macropore flow, and

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different management practices in the U.S. Midwest has thus far been limited.

In their summary of the NAWQA Program, Gilliom et al. (2006) reported that atrazine (and its metabolite deethylatrazine) was the single most frequently detected pesticide in streams and ground water, being detected greater than 90% of the time in streams and 42% of ground water samples in agricultural areas. In 1998 atrazine was detected in all 129 Midwestern stream and river water samples studied with median and maximum concentrations of 3.97 and 224 μg/L (Battaglin et al., 2000). Frequent detection of this herbicide is partly related to its high usage rate with approximately 23 million kg of atrazine applied to corn in the United States in 2010 (USDA, 2012). This high detection frequency may affect reproduction of aquatic flora and fauna, which impacts the whole aquatic ecosystem (e.g., Graymore et al., 2001). Concentrations of atrazine were greater than one or more aquatic-life benchmarks in 18% of agricultural streams in the multi-year national study (Gilliom et al., 2006). Furthermore, because drinking water with excessive levels of atrazine for many years could lead to cardiovascular system or reproductive difficulties, the Environmental Protection Agency set a maximum contaminant level (MCL) of 3 μg/L (USEPA, 2012).

Subsurface drains generally reduce pesticide transport in surface runoff because of increased infiltration (Kladivko et al., 2001). Also, the NAWQA Program found that the atrazine concentration in ground water was inversely correlated with artificial drainage, perhaps because drains divert atrazine to streams and rivers reducing atrazine transport below the "tile" drain depth (Stackelberg et al., 2012). Although subsurface drains can reduce atrazine transport in runoff and to ground water, atrazine is detected in streams at high concentrations in corn-belt states where it is heavily applied including Iowa, Illinois, Indiana, and western Ohio (Gilliom et al., 2006). Subsurface drains are also prevalent in these states (e.g., Jaynes and James, 2007).

Effective methods to reduce pesticide loss to subsurface drainage and leaching include application rate reduction, product substitution, and shift of the application date. However, the effects of tillage systems on pesticide transport are inconsistent, insufficiently known, and unpredictable (e.g., Reichenberger et al., 2007). The Root Zone Water Quality Model (RZWQM) is an agricultural system model that includes routines to simulate pesticide transport to subsurface drains, subsurface soil, shallow ground water, and macropore flow. Malone et al. (2003, 2004b) found that RZWQM successfully simulated the effects of tillage systems on pesticide transport: (1) using data from undisturbed soil blocks brought into the laboratory and (2) using data from a single season field study on a well drained soil. The associated model parameterization methods to simulate the effects of tillage systems on pesticide transport have not been tested for soils with subsurface drainage using multiple years of data.

In complex systems such as agriculture, models have been suggested as the only way to quantify the site specific effects of management practices across the array of interacting conditions often affecting the system (Ahuja et al., 2002). Malone et al. (2004c) concluded that in general RZWQM simulates pesticide fate reasonably well under many scenarios after extensive calibration and testing. However, field assessments of RZWQM simulated pesticide concentration in subsurface drainage under different application rates are lacking. In fact, little field research is available reporting pesticide concentrations in subsurface drainage under multiple application rates.

Pesticides can rapidly move from the soil surface to ground water due to preferential flow (e.g., Arias-Estevez et al., 2008). Goss et al. (2010) suggested that providing evidence of this mechanism is one of the most significant roles lysimeters have provided toward the development of our understanding of ground water contamination. Preferential flow has been defined as '. . .all phenomena where water and solute move along certain pathways, while bypassing a fraction of the porous matrix' (Clothier et al., 2006; Hendrickx and Flury, 2001). Recently, Tiktak et al. (2012) needed to modify the leaching model PEARL to include preferential flow to accurately simulate the rapid movement of pesticides to subsurface drainage. Likewise, Guzman and Fox (2012) showed that accurately representing preferential flow is very important to model pathogen and *E. coli* transport to subsurface drains using RZWQM.

Although more research is needed on the subject, RZWQM has been used to investigate the effects of tillage systems and preferential flow on atrazine movement in artificial subsurface drainage. Kumar et al. (1998) concluded that RZWQM showed high potential for predicting atrazine losses with subsurface drainage as affected by tillage systems when macropore flow was simulated. They reported higher simulated and observed atrazine loss to drain flow under no-till compared to moldboard plow systems, which was attributed to higher lateral saturated hydraulic conductivity under no tillage. Atrazine loss to drain flow is the product of atrazine concentration in drainage and drain flow volume. Therefore, the lateral saturated conductivity could affect the drain flow volume more than the atrazine concentrations in drain flow. Malone et al. (2003) attributed higher simulated and observed pesticide concentrations in leachate under no-till compared to tilled soil to parameters affecting the timing of macropore flow during rainfall. Because macropore flow occurred sooner after rainfall initiation in the no-till treatment, the result was higher pesticide concentrations in leachate.

The pesticide component of RZWQM was thoroughly revised subsequent to the initial release in 1992 (Wauchope et al., 2004). Concurrent with this revision, the model was tested using short-term field data under conditions without subsurface drainage (Malone et al., 2004b,c; Ma et al., 2004a). Few long term field tests (e.g., >3 years) of the revised pesticide component of RZWQM have been conducted and one of the only tests of the revised model under subsurface drainage used two field sites in Indiana with one year of data for model calibration and testing (Fox et al., 2007).

Investigating agricultural system model parameter sensitivity has been an important component of many research projects (e.g., Kumar et al., 1998; Ma et al., 2004b; Walker et al., 2000; White and Chaubey, 2005; Ahmed et al., 2007). Malone et al. (2001, 2004b) reported that the macropore parameters were among the most sensitive RZWQM inputs affecting simulated atrazine and metribuzin transport through well drained soil. In contrast, Kumar et al. (1998) found soil macroporosity among the least sensitive variables associated with RZWQM simulation of atrazine transport through poorly drained soil to subsurface drain flow. Few studies, however, have investigated the sensitivity of a wide range of RZWQM input parameters associated with simulated pesticide concentrations in subsurface drain flow. To facilitate model parameter optimization and sensitivity analysis, RZWQM was recently linked with the automatic parameter optimization program PEST (model independent parameter estimation; Doherty, 2004) that reports sensitivity indices of optimized parameters (Malone et al., 2010; Nolan et al., 2010). An additional benefit of using automatic calibration methods such as PEST is that they help provide an objective, defensible, and repeatable way to calibrate models with many parameters (Rose et al., 2007).

As discussed, management practices such as application rates and tillage systems can influence pesticide transport through soil, but the affect on pesticide transport to subsurface drainage is poorly understood. RZWQM can accurately simulate pesticide transport through macropores and has been tested under a variety of conditions, but the current model's ability to simulate pesticide concentrations and transport in subsurface drain flow over a long