Water Quality Impacts of Corn Production to Meet Biofuel Demands

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Abstract: The overall goal of this project was to quantify the long-term water quality impacts of land management changes associated with increased demands for corn as a transportation biofuel feedstock in the United States. A modeling approach that considers a nonpoint source model, Groundwater Loading Effects of Agricultural Management Systems and National Agricultural Pesticide Risk Analysis, was used to simulate annual losses in runoff, percolation, erosion, nitrate-nitrogen, total phosphorus, atrazine (1-chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine), and pyraclostrobin (Methyl {2-[1-(4-chlorophenyl)-1H-pyrazol-3-yloxymethyl] phenyl} methoxycarbamate) to the edge-of-field and bottom-of-root zones associated with multiple cropping scenarios. Model results for representative soils, throughout Indiana, were analyzed to determine 10% (worst case) and 50% (average case) probability of exceedence in the aforementioned water quality indicators. Modeling results indicated significant differences ($p < 0.05$) in water quality indicators between continuous corn and corn-soybean rotations. The results showed that agricultural management decisions would have greater impacts on nutrient, runoff, erosion, and pesticides losses from agricultural fields compared to water quality indicators associated with the projected changes in crop rotation systems. The model results point to the need for additional research to fully understand the water impacts of land management decisions associated with corn grain as a feedstock for biofuel production.

DOI: 10.1061/(ASCE)EE.1943-7870.0000095

CE Database subject headings: Fuels; Crops; Best Management Practice; Nutrients; Pesticides; Phosphorous; Nonpoint pollution; Water quality; Runoff; Hydrologic models.

Introduction

In recent years, high U.S. gasoline prices have prompted a renewed interest in alternative fuel sources to meet increasing demands, particularly by the transportation sector. This heightened interest in alternative fuel sources was projected to utilize ethanol as a primary fuel, meet fuel demands of the transportation sector, and reduce U.S. dependency on foreign oil. The use of ethanol with gasoline is not a new concept. In the United States, ethanol has been used since the 1990's as a gasoline additive replacing methyl tert-butyl ether. The federal government created numerous goals to phase in the use of ethanol in coming years. For instance, the Energy Policy Act of 2005 established the renewable energy standards with a goal to double production of ethanol to 7.5 billion gallons before the year 2012 (DOE 2005). The *Energy Independence and Security Act* (EISA) of 2007 was projected to have long-term impacts on U.S. agriculture which set a mandatory renewable fuels standard requiring fuel producers to use at least 36 billion gallons of biofuel by 2022 (U.S. Congress 2007). In addition, the 2008 RAND Corporation report examined the feasibilities of using renewable sources to produce 25% of transportation fuel and electric power by the year 2025 and noted that increased biomass production could be accompanied by adverse environmental impacts due to land conversion (Toman et al. 2008). It is anticipated that the U.S. agricultural sector, primarily the Midwest corn-belt states, will respond to these enormous challenges through the provision of raw materials for ethanol and serve as a key player in future renewable energy sources.

Although the 2007 EISA capped corn-grain ethanol at 15 billion gallons with 21 billion from cellulosic ethanol, the current high cost of large-scale cellulosic ethanol production made corn-based ethanol production (which remains the largest source of U.S. ethanol production) an immediate focus (Solomon et al. 2007; U.S. Congress 2007). In 2007, a shift from corn for food to corn for fuel increased both market prices and corn acreage in the U.S. to record levels of 93 million acres, representing a net increase of 12.1 million acres from 2006 (USDA-NASS 2007). This expansion to produce bioenergy by the agricultural sector is potentially poised to create unintended environmental consequences that are not yet fully understood. As an example, it was projected that increases in corn-based ethanol production would result in increased field applications of chemicals and fertilizers as well as less crop rotation with soybean (Simpson et al. 2008). In theory, over time, there would be increased nonpoint source pollutant loadings to water sources and other potential environmental and ecosystem impacts (Pimentel and Lal 2007; Pimentel and Patzek 2005; de Oliveira et al. 2005). A better understanding of the projected changes and their impacts to water quality is needed to develop cost effective management strategies to minimize the on-

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Note. This manuscript was submitted on June 11, 2008; approved on April 5, 2009; published online on May 30, 2009. Discussion period open until April 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Environmental Engineering***, Vol. 135, No. 11, November 1, 2009. ©ASCE, ISSN 0733-9372/2009/11-1123–1135/$25.00.

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and off-site water quality impacts. The limited focus given to the environmental impacts of biofuel production highlights a need for research to better understand those unintended consequences of increased U.S. corn production to meet ethanol demands.

Past studies, with emphasis on life-cycle assessment and anthropogenic greenhouse gas emission, have revealed mixed results regarding the benefits of corn-based ethanol. Researchers continue to argue the pros and cons, often with disregard to the environment, of the wide scale benefits of biofuels as a competitive substitute to fossil fuel (Pimentel and Lal 2007; Shapouri et al. 2003). For example, de Oliveira et al. (2005) suggested that corn-based ethanol would require that more acreage be devoted to corn production, which could have environmental impacts that outweigh its benefits. This increased acreage would potentially be obtained from lands already devoted to agriculture and not the conversion of forest lands, resulting in cropping systems shifts driven by high corn prices. Even though there is very limited information about the exact environmental impacts of biomass for biofuel production, these studies have pointed to potential environmental and ecosystem impacts. There is a need for in-depth studies to quantify those specific effects so that appropriate watershed management decisions can be taken.

The complexities of ecosystems create difficulties in understanding pollutant effects over a long term because relationships among system inputs and estimated losses are highly nonlinear (Delgado et al. 2005; Hansen et al. 2002; Liu et al. 1997). Therefore, it is often beneficial to use computer simulation models to represent “what-if” scenarios to provide quick answers regarding the long-term impacts relating to land management changes. Computer models represent an intermediate step in understanding changes in nonpoint source levels and may be useful prior to any in-field monitoring (Thomas et al. 2007). The use of computer models to forecast naturally occurring conditions (e.g., daily precipitation and hurricane paths) have become prevalent in the decision-making process of today’s society (Thomas et al. 2007). Models have been proven valuable in cases where data are limited or unavailable (Thomas et al. 2007). Computer simulation can reduce time, is relatively inexpensive, and is an environmentally safe technique to evaluate the effects of agricultural management practices on surface and subsurface water sources (Mahmood et al. 2002). A symbiotic relationship exists between models and measured data in the sense that models often need measured data so that stakeholders have a level of confidence in model predictions (Harmel et al. 2006). However, measured data are costly and time consuming to collect for every scenario of interest (e.g., annual weather variability, spatial location of practice, scale effects from edge-of-field zone to downstream).

The objectives of this work were to: (1) quantify long-term changes in runoff, percolation, erosion, nutrients, and pesticides to the edge-of-field and bottom-of-root zones due to cropping system changes; (2) assess losses of pesticides that can be expected from agricultural fields statewide due to increased corn production in existing row-crop areas; and (3) evaluate emerging water quality implications from application of new pesticides applied to meet corn production demands for biofuels. The quantified estimates would provide insight to the following question: What are the unintended consequences to water quality due to large-scale biomass demand?

Methodology

A modeling framework was used to evaluate water quality impacts of land management options as influenced by increased corn-based biofuel production in the Midwest. The nonpoint source pollution model, Groundwater Loading Effects of Agricultural Management Systems and National Agricultural Pesticide Risk Analysis model (GLEAMS-NAPRA), was used to simulate long-term (32 years) runoff, percolation, nitrate-N, total phosphorus (TP), atrazine (1-chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine), and pyraclostrobin (Methyl {2-[1-(4-chlorophenyl)-1H-pyrazol-3-yloxymethyl] phenyl} methoxycarbamate) annual losses to the edge-of-field and bottom-of-root zones based on the most current changes in agronomic practices associated with corn and soybean production (Table 1). A shift from the current corn-soybean rotation to increased corn production was evaluated by considering two different cropping systems: 2 years of corn production followed by 1 year of soybean rotation, and continuous corn. In order to minimize the impact of interannual climate variability on hydrologic/water quality output, all possible permutations of crop rotations within each scenario were evaluated (Table 1). It was assumed that corn stover was not removed with harvesting of corn which is consistent with current harvesting practices. In Indiana, the common tillage practice is to alternate tillage systems with crop rotation, i.e., no-till soybeans with conventional tillage corn (ISDA 2008). Tillage practices representative of Indiana producers including conservation tillage, continuous no-till and conventional tillage were simulated in this study.

Table 1. Cropping System Scenarios Used to Simulate Water Quality Impacts with GLEAMS-NAPRA from Increased Demands for Corn-Based Ethanol

	Simulated tillage systems		
Cropping systems	Conservation tillage	Conventional tillage	No till
Corn-soybean (cs)	SD[a], NT[b]	FC-SD[c]	NT
Soybean-corn (sc)	NT,SD	FC-SD	NT
Corn-corn-soybean (ccs)	SD, FC-SD, NT	FC-SD	NT
Soybean-corn-corn (scc)	NT,SD,FC-SD	FC-SD	NT
Corn-soybean-corn (csc)	FC-SD,NT,SD	FC-SD	NT
Corn-corn-corn (mL)	FC-SD, FC-SD, FC-SD	FC-SD	NT

[a] Spring disk.

[b] No till.

[c] Fall chisel, spring disk.

To simulate nutrients, fertilizer application rates followed Tri-state recommendations for corn which varied according to soil type due to crop potential yields (Vitosh et al. 1995). Other management inputs such as planting, harvesting and crop maturity dates were obtained from the Indiana Agricultural Statistics reported crop production summaries to National Agricultural Statistics Service (Table 2).

GLEAMS Model Description

The Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model is a computer program developed to simulate the edge-of-field and bottom-of-root zone loadings of water, sediment, pesticides, and plant nutrients (Leonard et al. 1987). Fig. 1 illustrates the physical system and processes represented in GLEAMS. Hydrology, erosion, nutrient, and pesticides are major components used by the GLEAMS model. These components can simulate the effects of cropping systems on surface and ground water quality on a daily basis using climate, soil, and

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Table 2. Management Inputs Represented in GLEAMS-NAPRA Simulations

Description	Corn input	Soybean input
Planting date	May 6	May 15
Harvest date	October 14	September 10
Maturity date	September 15	October 1
Tillage	Conservation and conventional	Conservation and conventional
Root zone depth	76 cm	76 cm
Slope length	30 m	30 m
Fertilizer		
Nitrogen fertilizer type	Anhydrous ammonia (injected)	—
Phosphorus fertilizer type	Triple superphosphate (incorporated)	—
Fertilizer application rates	Tri-state recommended rates[a]	—
Date of application	May 6 (at planting)	—
Pesticide		
Herbicide: type	Aatrex (42.6% atrazine)	—
Application rate	2.24 kg a.i. ha^{-1} (broadcast)[b]	—
Application date	May 6	—
Foliar fraction	0%	—
Fungicide: type	Headline (active ingredient pyraclostrobin)	—
Application rate	0.22 kg a.i. ha^{-1} (surface application)[b]	—
Application date	July 1	—
Foliar fraction	100%	—

[a] Tri-state fertilizer recommendations computes corn fertilizer application rates as a function of potential crop yield (Vitosh et al. 1995).

[b] Label rates.

management data inputs (Leonard et al. 1987). The hydrology component of the model is based on the modified USDA-SCS curve number (CN) procedure and a soil moisture accounting technique that considers moisture depletion as influenced by rainfall and evapotranspiration (Williams and LaSeur 1976). The model uses CN only at the beginning of the simulation process and incorporates various hydrological processes, such as infiltration, runoff, soil evaporation, plant transpiration, rainfall/irrigation, snow melt, and soil water movement, within the root zone to calculate water balance (Leonard et al. 1987).

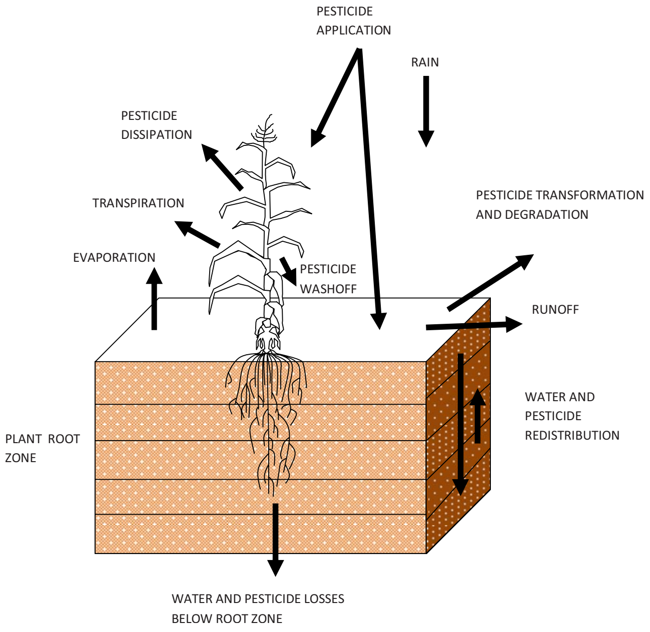

Fig. 1. The physical system and processes represented in GLEAMS [modified from Leonard et al. (1987)]

The National Agricultural Pesticide Risk Analysis (NAPRA) model uses GLEAMS as the core model to simulate nutrient loadings to surface and shallow ground water. The internet version allows users to run the model from remote locations to perform simulations with a simpler interface (Lim and Engel 2003; Bagdon et al. 1994). The postprocessor of the NAPRA model aggregates and converts GLEAMS output into time series data which can be externally linked to GIS layers associated with soil units (Thomas 2006).

Model Inputs

Management practice, climatic data, and soils are input information required by GLEAMS to simulate nutrients and pesticides. The GLEAMS model allows users to control selected nutrient input requirements including crop rotation information, pesticide, and fertilizer application rates, source, and method of application (Knisel and Davis 2000). The following subsections provide additional details about these model inputs.

Fertilizer and Pesticide

Fertilizer application rates were based on Indiana's Tri-state recommendations for corn, which base fertilizer application rates as a function of potential corn yield and crop produced in the preceding year. Potential corn yields from the State Soil Geographic (STATSGO) soil database were adjusted, based on a methodology presented by Thomas et al. (2007), to account for development of new cultivars, improved technology, and agronomic practices. The Tri-state recommendation for nitrogen application rates suggests reducing nitrogen fertilizer application rates by 34 kg/ha

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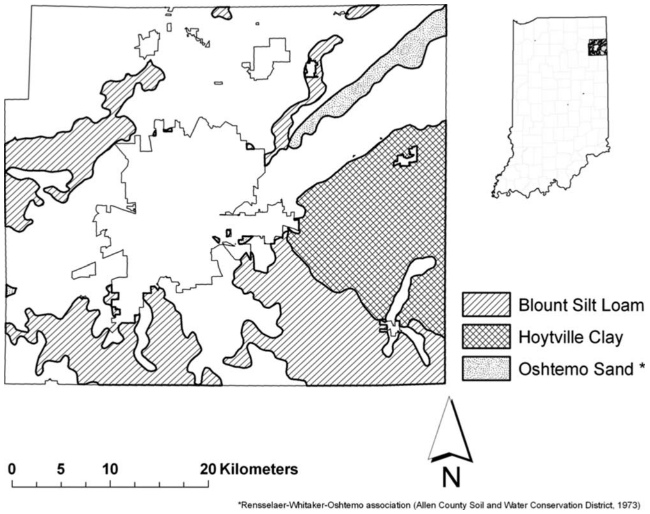

*Rensselaer-Whitaker-Oshtemo association (Allen County Soil and Water Conservation District, 1973)

Fig. 2. Distribution of the three contrasting textured soils (Blount silt loam, Hoytville clay, and Oshtemo sand) in Allen County, northeast Indiana

when corn follows soybean and 0 kg/ha when corn follows corn (Vitosh et al. 1995). In all modeling scenarios, fertilizer and the herbicide (atrazine) were not applied to soybean, a practice common to the region. It was assumed that 100% of the applied atrazine contacted bare soils and was not intercepted by residue or vegetation. Typically, glyphosate [N-(phosphonomethyl) glycine] is the herbicide of choice for soybeans and was not considered in this study due to its low potential to impact water quality (Borggaard and Gimsing 2008).

A single application of foliar fungicide (pyraclostrobin) at tasseling (crop height 1.8 m) was the common practice with Indiana corn production and was adapted for model simulation. Foliar fungicide usage on soybean was not considered in this study although it was approved for emergency use to combat Asian soybean rust (*Phakopsora pachyrhizi* Sydow), a disease that was first reported in the United States in 2004 (Bradley and Sweets 2008). The model accounted for aerially applied pesticide by fractioning interception between crop foliage and soil, which are both degraded differently (Leonard et al. 1987). In model simulations, it was assumed that at the time of fungicide application, the foliage, or crop canopy would fully cover soil surfaces causing a 100% canopy interception.

Soils and Climate

GLEAMS output is influenced by complex climate-soil interactions. The current GLEAMS-NAPRA model allows users to select soil characteristics based on information available in the National Soil Information System (NASIS) database for soils of the Natural Resources Conservation Service (NRCS) in the United States. Physical soil parameters such as texture, porosity, field capacity, and organic matter content were obtained from soils' databases. Regional model simulations were based on three major soil types representative of agricultural lands in Allen County, northeast Indiana (Fig. 2) and were predominantly sand, silt, or clay (Table 3). Soils data are input by the soil horizon with values for porosity, water retention characteristics, and organic matter distributed to the computational layers. For statewide pesticide mapping purposes, the NRCS STATSGO (1:250,000), a digital soil geographic database, was used since it contains both spatial and tabular data on soils throughout Indiana, as opposed to NRCS NASIS which contains only tabular data (USDA-NRCS 1995, 2007). The erosion component of the model is a dynamically driven process. The model uses the Universal Soil Loss Equation (Wischmeier and Smith 1978) to compute overland erosion potential based on soil and hydrology information. Soil physical and chemical properties are entered both in the hydrology and erosion components of GLEAMS, which outputs erosion estimates with each simulation.

Continuous daily precipitation and temperature were required climatic inputs for the GLEAMS-NAPRA model (Knisel and Davis 2000). In statewide simulations, the widely used stochastic daily climate generator model, CLIGEN (Nicks et al. 1995), was used to generate the model's climatic inputs, based on measured historic data from a climate station (39°45′00″N, 86°07′12″W)

Table 3. Physical Properties and Commercial Fertilizer Application Rates for Blount Silt Loam, Hoytville Clay, and Oshtemo Fine Sandy Loam Soils in Allen County, Indiana

	Soil map unit, Name		
Soil map unit, Name[a]	BmB2, Blount	Hs, Hoytville	OfB, Oshtemo
Hectares (ha)	2,011	22,984	630
Depth (cm)	0–23	0–18	0–36
Hydrologic soil group	C	C	B
K factor	0.43	0.20	0.20
Percent sand (%)	20	5	72
Percent silt (%)	60	52	19
Percent clay (%)	20	43	9
Moist bulk density (g/mL)	1.30–1.60	1.30–1.6 0	1.40–1.70
Slope (%)	2–6	0–2	2–6
Potential corn yields[b] (Mg ha^{-1})	8.4	10.4	7.9
Nitrogen fertilizer application rate[c], corn follows corn (kg ha^{-1})	172	221	161
Nitrogen fertilizer application rate, corn follows soybean (kg ha^{-1})	138	187	128
P_2O_5	41	52	39

[a] The USDA-NRCS soil-database.

[b] Thomas et al. (2007).

[c] Tri-state fertilizer recommendations computes corn fertilizer application rates as a function of potential crop yield (Vitosh et al. 1995).

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in Marion County (center of the State of Indiana) for the simulation period. Sinha and Cherkauer (2008) studied the climatic variations for three sites located in northern, central, and southern Indiana for the period 1967–2006 and observed small variations in annual precipitation. The average annual precipitation for northern, central and southern Indiana sites were 94.4 cm (SD 14.5 cm), 95.1 cm (SD 11.9 cm), and 119.8 cm (SD 20 cm), respectively (Sinha and Cherkauer 2008). These findings suggested that the use of multiweather stations for statewide model simulations would not create any noticeable changes and as such the use of a single weather station was sufficient for the focus of this study.

CLIGEN was used to produce continuous daily climate files and is used by many field-scale as well as watershed models such as Water Erosion Prediction Project (Baffaut et al. 1996; Nicks et al. 1995) and the Soil and Water Assessment Tool (Arnold et al. 1998). However, observed climatic data obtained from a weather station in Allen County was used for the 3 studied textured soils and was available in the model's database.

Model Simulations and Data Extraction

For each soil unit, continuous daily simulation of the complex soil-climate-management interaction was performed for a 32-year period using the previously described model inputs. In previous studies, the model was calibrated and validated for locations throughout Indiana and has been found to perform satisfactory, based on acceptable Nash-Sutcliffe coefficients (Engel et al. 2007; Adeuya et al. 2005; Nash and Sutcliffe 1970). The American Society of Civil Engineers Task Committee recommended the Nash-Sutcliffe coefficient, or coefficient of simulation efficiency, as a basic goodness of fit criterion for evaluating model performance (ASCE Task Committee 1993). Engel et al. (2007) presented a procedure for standard application of hydrologic/water quality models and suggested that model performance can be judged satisfactory if the Nash-Sutcliffe coefficient was greater than 0.4. In the calibrated and validated study, GLEAMS-NAPRA simulations with similar soil association within the Driesbach watershed (northeast Indiana) yielded Nash-Sutcliffe model efficiencies of 0.89, 0.78, 0.69, 0.57, and 0.70, for monthly runoff, sediment, nitrate, sediment phosphorus, and total phosphorus, respectively. The model was also validated for pesticide (atrazine) losses and performed satisfactorily on Clermont Silt Loam soil in Indiana (Sichani et al. 1991). Consequently, these studies indicate that the model, for the purpose of simulating the effects of alternative management systems, did not require additional calibration and validation work (Knisel et al. 1991). The batch run capabilities of the model allowed the performance of statewide simulations for selected water quality parameters. Subsurface drainage, a common regional water management practice on poorly drained soils such as Hoytville clay, was not accounted for in model simulations (Kladivko et al. 2001).

The tabulated GLEAMS-NAPRA raw outputs were summarized in annual estimates and were exported in multiple file formats which then served as input files from which the 10 and 50% probability of exceedence were obtained using a function written in MatLab software, version 7.1 (MathWorks, Inc., Mass.).

Statistical Analysis

Exploratory data analysis was performed to evaluate the distribution of annual estimates related to the cropping systems. This was done to ensure that assumptions or constraints of statistical procedures were not violated. For example, the validity of parametric tests such as Analysis of Variance (ANOVA) requires that the data follow a normal distribution with constant variance (Montgomery 2004). If the model assumptions of normality and constant variance were violated, then logarithmic transformation was applied to the data prior to ANOVA testing. ANOVA tests ($\alpha = 0.05$) determined if there were significant differences among the three cropping practices, using the water quality metrics mentioned in objective one as the input data set. The ANOVA analyses in conjunction with two multiple comparison tests were generated using SAS/STAT software, version 9.1.3 (SAS Institute Inc., N.C.). In keeping with a general statistical approach, both Tukey and Bonferroni multiple comparison tests were used when the null hypothesis of the ANOVA test was rejected, so as to determine the population means that was statistically similar (Montgomery 2004). As an additional step, orthogonal contrasting, a linear combination technique, was used to compare cropping practices whose means were statistically significant (Montgomery 2004).

Results and Discussion

The results presented below focus on crop rotation shifts and two types of tillage operations: conservation tillage and conventional tillage. Model results with no-till provided similar results and, therefore, are not presented here for brevity. A risk-based approach is used to present results as worst-case (10% probability of exceedence, extreme years) and average case (50% probability of exceedence, average years) scenarios. The results are summarized as 1-year corn-soybean rotation (cs), corn-corn-soybean rotations (ccs) and continuous corn (cc). Corn-soybean (cs) and soybean-corn (sc) annual estimates are averaged and reported in this section as corn-soybean (cs), while the combinations of corn-corn-soybean (ccs), corn-soybean-corn (csc) and soybean-corn-corn (scc) are averaged and reported in this section as corn-corn-soybean (ccs).

Impacts on Hydrology

In worst-case scenarios, trends in the annual estimated runoff losses among cropping systems were similar across soil types (Fig. 3); however, percolation losses were significantly greater for corn-soybean (cs) and corn-corn-soybean (ccs) rotations compared to continuous corn (cc). Average-case scenarios revealed similar trends as shown in worst-case scenarios: no significant differences in annual runoff losses among cropping systems; significantly greater percolation losses with corn-corn-soybean and corn-soybean compared with continuous corn. Even though no statistical differences were observed in percolation estimates as affected by crop rotation, in average-case scenarios, corn-corn-soybean had slightly greater percolation estimates (125, 236, and 234 mm) than corn-soybean values (105, 227, and 230 mm). Contrarily, in worst-case scenarios, corn-soybean had slightly greater percolation estimates (216, 344, and 358 mm) than corn-corn-soybean across soils (196, 329, and 345 mm). There were no clear reason for the noted differences; however, this indicates that average-case events do not necessarily follow the same pattern as worst-case (extreme) scenarios. Another interesting observation was the role of topography in runoff generation that was often ignored in theoretical assessments of water movement within different soil textures. As indicated by Fig. 3, Blount silt loam

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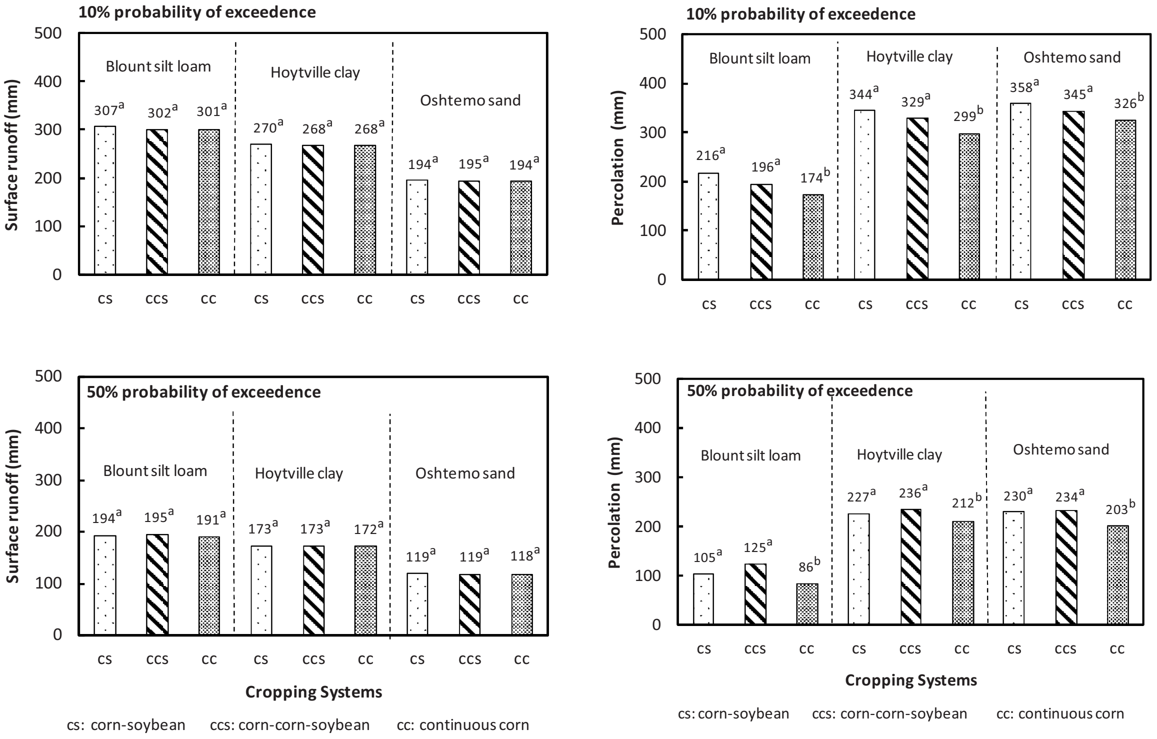

Fig. 3. Annual estimates in surface runoff and percolation below the root zone from multiple cropping systems based on long-term (32 years) model simulation. Within each soil, values followed by the same letter are not significantly different at the 5% level.

(2–6% slope) had slightly higher runoff losses than Hoytville clay (0–2% slope) due to differences in slope, even though other soil properties, such as bulk density, hydrologic soil group, and soil depth are similar (Table 3).

The results were consistent with other studies that have shown that cropping and tillage were two factors that slightly influenced surface runoff (Ghidey and Alberts 1998). In Missouri, Ghidey and Alberts (1998) measured runoff from seven cropping systems and tillage treatments on silt loam soil over a 12-year period and noted that mean annual runoff from soybean were 3–12% higher than corn. Ghidey and Alberts (1998) also found that conservation tillage plots had a lower saturated hydraulic conductivity and a higher bulk density and soil water content when compared with conventional tillage plots. The study concluded that cropping systems had little effect on annual runoff and that no-till had significantly greater surface runoff than conventional tillage (Ghidey and Alberts 1998). No-till system influences high soil moisture content that will increase annual runoff estimates created by saturation excess. Cropping systems influence available soil residue which would affect infiltration and surface runoff. Typically, little residue remains on the ground following soybean as opposed to corn production. It can be expected that insufficient residue would cause soils to be easily detached following rainfall events while increasing the volume of surface water.

The results from this study indicate that shifting acreage to increase corn production to meet biofuel demands may not significantly affect annual runoff losses. However, a shift to continuous corn production may create significantly smaller annual percolation below the root zone when compared with corn-corn-soybean and corn-soybean rotations. A high evapotranspiration rate with continuous corn production influenced the reductions noted in runoff and percolation losses. Evapotranspiration is an important process in chemical fate and transport simulation (Ma et al. 1999).

Impacts on Erosion

Fig. 4 shows annual estimates in water erosion losses to the edge-of-field zone from three cropping systems evaluated in this study. The estimates shown in Fig. 4 were within range (0.22–6.72 t/ha) of surveyed no-till and soil loss trends from Indiana cropland (1990–2007) representing at least 450 fields (ISDA 2008). The model estimates suggest that increasing corn production, under the given tillage systems, would result in increased soil loss from agricultural lands. As shown in Fig. 4, in worst-case scenarios, annual estimated erosion losses were highest on Blount silt loam (2–6% slope) with 6.55, 7.32, and 7.50 t/ha of soil loss for corn-soybean (cs), corn-corn-soybean (ccs), and continuous corn (cc), respectively. Hoytville clay (0–2% slope), the more prominent soil type in northeast Indiana, had the lowest estimates in erosion losses to the edge-of-field zone, in worst case scenarios, with values 0.59, 0.58, and 0.72 t/ha for corn-soybean (cs), corn-corn-soybean (ccs), and continuous corn (cc), respectively. Although estimated quantities varied across cropping systems, there were no significant differences ($p < 0.05$) in mean annual estimated erosion losses from corn-soybean and corn-corn-soybean systems.

Erosion estimates varied across soils and were influenced by soil texture, slope-length, and tillage systems. The susceptibility of a soil to erode is often quickly assessed by the erodibility factor (K factor) (Baskan and Dengiz 2008; Parysow et al. 2003). The model results indicate that slope could play a greater role in annual soil loss estimates than the erodibility potential factor (K factor). Blount silt loam had the greatest potential to erode ($K = 0.43$), with a 2–6% slope, and produced highest annual estimates in annual soil loss associated with overland flow. If assessment was based only on soil erodibility factor, Hoytville clay ($K = 0.20$) would have a slightly greater potential to erode than Oshtemo fine sandy loam ($K = 0.17$). However, as shown in Fig. 4,

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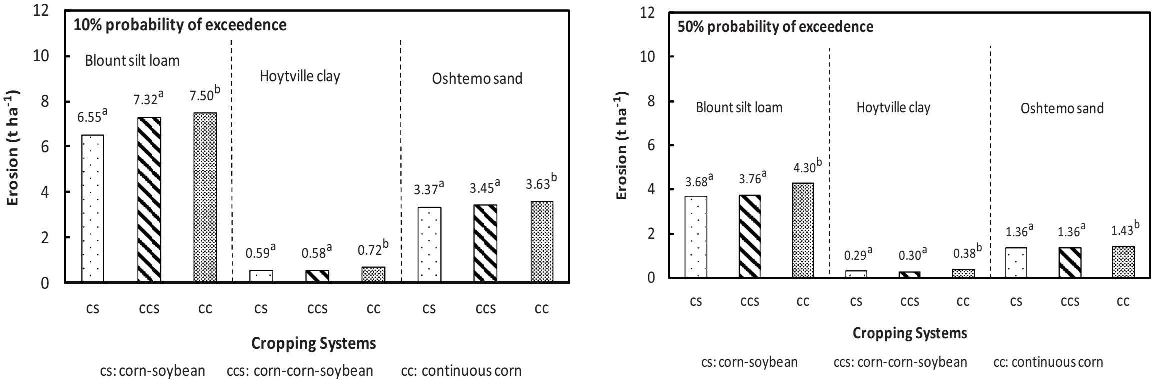

Fig. 4. Estimates in annual erosion based on GLEAMS-NAPRA simulation of multiple cropping systems under conventional tillage corn and no-till soybean. Within each soil, values followed by the same letter are not significantly different at the 5% level.

Oshtemo fine sandy loam, with a 2–6% slope, produced greater estimates in annual soil loss to the edge-of-fields and indicates that erosion generation can be driven by other processes such as slope-length (LS-factor) and crop cover (C-factor), and crop management (P-factor), which were accounted for by the model.

Soil loss is an important component in understanding biofuel production impacts on the environment because persistent agrochemicals often attach to soil particles and, overtime, biomagnify and bioaccummulate up the food-chain posing risks to higher species. Typically, sediment bound compounds go undetected because current government monitoring systems focus on in-stream concentrations of dissolved chemicals. Consequently, particulate bound chemicals are often assumed not to be an environmental issue. The current dominant practice of corn-soybean rotation produced the least annual estimated erosion suggesting that shifts to continuous corn, even with corn stover left in field after grain harvest, would result in greater soil losses. This problem can potentially be exacerbated when corn stover is removed from fields. For example, cellulosic ethanol production would influence the removal of corn stover (crop residue) for feedstock; thereby, potentially causing even greater soil losses. Studies have shown that no-till systems were likely to reduce erosion losses on intensively managed agricultural landscapes (Shipitalo and Owens 2006; Chaplot et al. 2004; Tan et al. 2002). The quick remedy that employs the use of no-till on corn systems may not be the final solution to reducing soil loss due to the following: no-till was not a popular practice with corn due to reduced yields experienced by Indiana producers; potential poor crop growth under no-till systems would also reduce soil protection from water erosion (Mamo and Bubenzer 2001; Azooz et al. 1995).

The United States Department of Agriculture's Conservation Reserve Program (CRP) provides support to address soil, water, and natural resources concerns on marginal and highly erodible croplands by removing them from row crop production and plants conservation vegetation such as switchgrass (*Panicum virgatum*). High demands for corn to produce ethanol would influence some producers to return those highly erodible conservation lands to corn production. Such conversion of sensitive CRP areas from protective vegetation to corn would potentially reverse water quality benefits of CRP lands. Studies have shown that soil aggregate stability gradually decreases when CRP lands were returned to crop production by conventional tillage (Huang et al. 2002). A decrease in aggregate stability would result in greater erosion potential of soils. The model results suggest that CRP acres returned to continuous corn would experience significantly higher erosion losses to the edge-of-field zone; thereby, creating potentially negative water quality impacts from sediments and particle bound pollutants. On conservation lands, estimated annual erosion losses were projected to be greater than worst-case (7.50 t/ha) and average-case (4.30 t/ha) estimated erosion losses for Blount silt loam soils, with continuous corn cropping, due to greater slopes and *K*-factors combined with differences in soil texture and bulk density.

Impacts on Nutrients

Annual estimates in nitrate-N and total phosphorus losses from varying cropping systems are shown in Figs. 5 and 6, respectively. Although fertilizer application rates varied, all three soils showed consistent trends in annual estimated nitrate-N losses to surface runoff from cropping systems. Across the three soils, continuous corn had higher estimated annual losses (9.51, 7.16, and 4.74 kg/ha) to surface runoff than corn-corn-soybean (7.41, 6.18, and 4.37 kg/ha) and corn-soybean systems (6.48, 5.73, and 3.98 kg/ha), under worst-case scenarios. Simulation of nutrient concentration losses indicated that nitrate-N concentrations were below the drinking water standard of 10 mg/L for all three cropping systems evaluated in this study. The detailed concentration values for different crop rotations and soil types are not presented here for brevity. It was interesting to note that although Tri-state fertilizer application rates recommended approximately 50 N kg/ha more of commercial fertilizer on Hoytville clay when compared with Blount silt loam (see Table 3), annual estimated nitrate-N losses were lower on Hoytville clay (Fig. 5). The relationship between fertilizer application rates and nutrient losses followed a nonlinear relationship (Delgado et al. 2005; Hansen et al. 2002). The model results suggested that high fertilizer application rates do not necessarily translate to high annual nitrate-N runoff losses due to varying soil properties and slope. As an example, Hoytville clay was a higher potential crop yielding soil (Table 3) with a relatively flat slope (0–2%) requiring greater fertilizer application rates; however, Blount silt loam with a 2–6% slope and lower fertilizer application rates had greater estimates in nitrate-N losses. Statistical analysis of the mean annual estimated nitrate-N losses to surface runoff revealed that cropping systems losses were significantly different ($p < 0.05$) with significantly higher ($p > 0.05$) mean annual losses from continuous corn compared with corn rotation systems.

Annual estimates in total phosphorus losses followed a similar trend with cropping systems across soils, where greater annual

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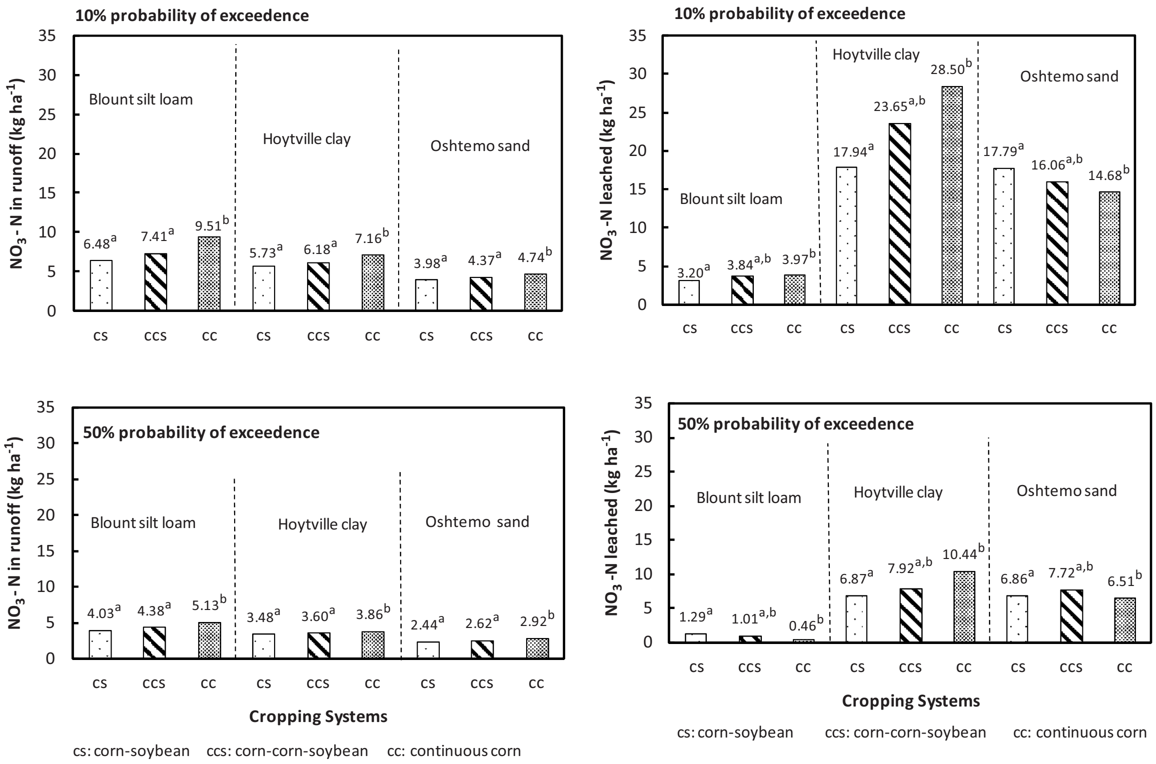

Fig. 5. Estimates in annual nitrate losses to surface and shallow ground water under conservation tillage rotation systems and conventional tillage continuous corn. Within each soil, values followed by the same letter are not significantly different at the 5% level.

losses were obtained from continuous corn (Fig. 6). Estimates in annual total phosphorus losses were greater under a continuous corn system as opposed to corn-corn-soybean and corn-soybean rotation systems. Tillage practices were likely to influence annual erosion and TP losses from agricultural fields because the greater portion of TP was sediment bound and transported with eroded soils.

The results suggested that a shift to continuous corn would significantly increase losses in nitrate-N and TP in surface runoff. Continuous corn systems demand greater commercial fertilizer input than rotation systems and as a result had higher estimated nitrate-N losses for both worst- and average-case scenarios. Agronomic fertilizer applications recommended application rates with potential crop yield related to various soil types and provide credit when corn follows soybean to account for fixed N to soil by soybean. Nitrate-N losses throughout the State would be higher than simulated estimates for fields that overapply fertilizer to boost crop yields (Thomas et al. 2007). The nutrient loss results imply that cropping system shifts due to increased corn production for corn-based ethanol would result in higher estimates in nitrate-N and TP to the edge-of-field. If the push to corn-based ethanol production continues, greater commercial fertilizer input would be required by agricultural producers while increasing demands for fossil fuel such as natural gas used to produce fertilizers. In the United States, natural gas comprises approximately 90% of the manufacturing cost of fertilizer such as anhydrous ammonia (Fee 2006). This would potentially prolong U.S. dependence on fossil to persist because of increased fertilizer usage, a necessary input in corn production. Projected nutrient losses from intensively managed agricultural landscapes could be increased with increasing demands for corn-ethanol. However, management systems such as conservation tillage could reduce nutrient losses.

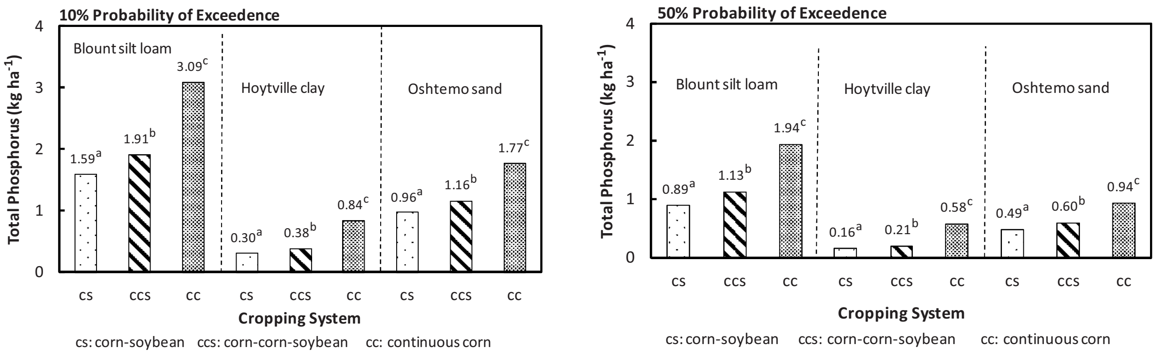

Fig. 6. Annual estimates in total phosphorus losses obtained from GLEAMS-NAPRA simulations of multiple cropping systems. Within each soil, values followed by the same letter are not significantly different at the 5% level.

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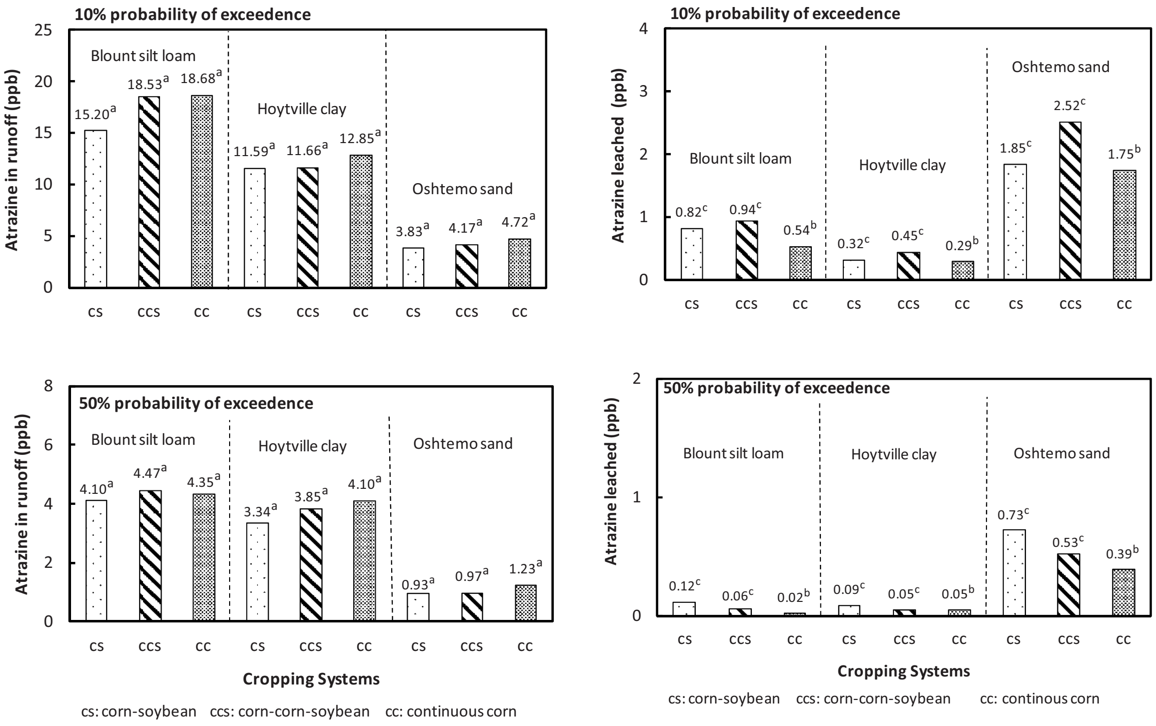

Fig. 7. Estimates in annual atrazine concentration losses to surface and shallow ground water based on long-term (32 years) GLEAMS-NAPRA simulation of multiple cropping systems on Blount silt (2–6% slope), Hoytville clay (0–2% slope), and Oshtemo sand (2–6% slope) under conservation tillage rotation systems and conventional tillage continuous corn. Within each soil, values followed by the same letter are not significantly different at the 5% level.

Previously, researchers have shown that potential nutrient losses from intensively managed agricultural landscapes can be mitigated with numerous best management practices such as terraces, grassed waterways, contouring, and conservation tillage (Secchi et al. 2007; Hansen et al. 2002).

Impacts on Pesticides

Fig. 7 shows annual estimates in atrazine concentration losses to the edge-of-field and bottom-of-root zones from multiple cropping systems under conservation tillage rotation and conventional tillage continuous corn. As shown in Fig. 7, highest annual atrazine losses to surface water were on Blount silt loam and Hoytville clay soils. Oshtemo sand had higher concentration losses to ground water, even though the levels were below the drinking water standards of 3 ppb. In worst-case scenarios, atrazine concentration losses to the edge-of-field were five times the drinking water standard of 3 ppb for Blount silt loam, approximately four times the standard for Hoytville clay and slightly above the standard for Oshtemo sand (Fig. 7). In average-case scenarios on Blount silt loam and Hoytville clay, annual atrazine concentration losses to surface water were projected to be slightly above the drinking water standard; however, estimates from Oshtemo sand could potentially be less than half the drinking water standards. Despite slight differences in quantified estimates among cropping systems, statistical analysis suggests that there were no significant differences ($p < 0.05$) in atrazine losses with surface runoff. However, mean annual estimated atrazine losses to ground water were significantly different ($p > 0.05$) for rotation systems compared to continuous corn. Similar results were observed with field studies conducted by Kanwar et al. (1997).

Soil-climate interactions were factors that influenced pesticide losses from agricultural fields with highest chemical concentrations occurring within two months following application (Kladivko et al. 2001). Physical soil properties and slope influenced the transportation pathways of water, as well as the transport mechanism of the highly mobile atrazine. As indicated by model results, poor drainage as well as saturation excess would increase surface runoff and was the main reason that Blount silt loam and Hoytville clay had higher atrazine concentrations in surface water compared to the ground water. Higher infiltration rates on Oshtemo sand would partition greater amounts of precipitation to ground water causing mobile compounds such as atrazine to be higher in leached groundwater. Previous studies in relatively flat watersheds (<3% slope) observed slightly greater atrazine losses in surface runoff than in subsurface discharge (Gaynor et al. 1995; Logan et al. 1994). Adsorption or partitioning coefficient (K_{oc}) was the primary pesticide property that influenced the mobility of chemicals with surface runoff or discharge below the root zone (Bakhsh et al. 2004). The K_{oc} of atrazine (100 mg/l) suggested that it is highly mobile and is less likely to sorb to soils and would be greater in surface water concentration loss than subsurface drainage (Kladivko et al. 2001; Southwick et al. 1990). This indicates that the modeling approach provided an appropriate description of atrazine losses from agricultural fields (Sichani et al. 1991).

Fig. 8 shows the average annual atrazine losses for Indiana. The greatest losses exceeding >6 ppb/year were concentrated in east-central Indiana. The soils in these areas are characterized by relatively poorly drained, clayey, and loamy soils, with high conventional tillage and heavy chemical use (Quansah et al. 2008). Historically, cities in the region of highest atrazine losses to surface water (Fig. 8) have measured levels that exceeded the EPA's

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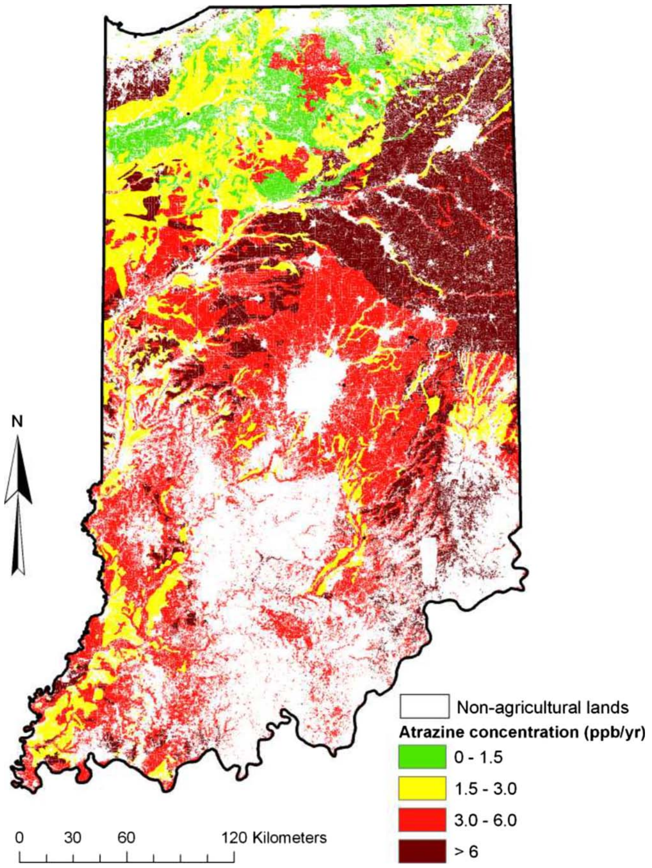

Fig. 8. Statewide annual estimates in atrazine concentration to the edge-of-field zone based on long-term weather (60 years) using an atrazine application rate of 2.24 kg a.i/ha (manufacturer's label rate) under conventional tillage continuous corn

maximum contaminant level of 3 ppb for public drinking water supplies. This was of major concern since approximately 48% of Indiana's drinking water comes from surface water supplies (Johnson et al. 2006).

However, further studies are required to better understand and quantify levels of water quality impacts with residue removal as a land management option. In average-case scenarios, simulation results revealed that soil incorporation of atrazine, as a best management practice, would reduce losses to surface water from 13 to 67% across cropping systems (see Table 4) on the three soils. Reductions were more drastic in worst-case scenarios where annual estimated losses to surface water ranged from 58 to 80% across cropping systems (see Table 4) on the three soils. These findings were consistent with a Midwest study, Management Systems Evaluation Areas project, which revealed that the incorporation of atrazine into the first two inches of soil reduced atrazine losses up to 75% compared with surface applications (Smith et al. 1999).

Emerging Pesticide Usage and Concerns

Land management systems are constantly adjusting due to changes in technology and/or cost of crop production inputs. A number of emerging land management practices are likely to change the aforementioned results associated with regional pesticide concerns. Since 2004, Indiana acreage of biotech (e.g., herbicide tolerant) corn has shown an upward trend (USDA-NASS 2007). Generally, glyphosate [N-(phosphonomethyl)glycine] is the postemergent herbicide of choice on herbicide-tolerant corn fields, such as Roundup Ready Corn. Increase usage of herbicide-tolerant corn potentially translates to decrease atrazine usage as well as estimated annual atrazine losses to surface and ground water sources (USDA-NASS 2007; USGS 2006). If trends continue to show an increase, this would reduce some of the projected broad-scale water quality effects of atrazine.

Another emerging issue relates to the use of foliar fungicides, such as pyraclostrobin, to increase corn yields when very little disease was present (Greg Shaner, personal communication, February 15, 2008). Laboratory studies in the U.K., required for pesticide registration, revealed that pyraclostrobin has a high toxicity to aquatic organisms and as such may be potentially damaging to aquatic ecosystems (Bartett et al. 2001). One U.S. toxicity study examined the acute toxicity of fungicides to glochidia and juvenile life stages of freshwater mussels (*L. siliquoidea*) and revealed a relatively high sensitivity of *L. siliquoidea* to pyraclostrobin, which is a rising concern to federal agencies such as the U.S.EPA and the Office of Indiana State Chemist (Bringolf et al. 2007).

As provided by model simulations, Fig. 9 shows annual estimates in pyraclostrobin losses with surface runoff and sediments based on a single application to corn under varying cropping scenarios. The crop growth stage (crop height approximately 1.8 m), aerial application, and application timing influenced the transport and degradation of the pesticide (Himel et al. 1990; Leonard et al. 1987). Foliar applied pesticides are not subjected to the same

Table 4. Estimated Annual Atrazine Losses to Surface Water Obtained from GLEAMS-NAPRA Simulations of Pre- and Post-BMP Application Methods on Blount Silt Loam, Hoytville Clay, and Oshtemo Sand Soils

	Blount silt loam			Hoytville clay			Oshtemo sand		
	cs[a]	ccs[b]	cc[c]	cs	ccs	cc	cs	ccs	cc
Pre-BMP atrazine losses, 50% POE[d] (ppb/yr)	4.10	4.47	4.35	3.34	3.85	4.10	0.93	0.97	1.23
Post-BMP (incorporation) losses, 50% POE (ppb/yr)	2.11	2.19	2.64	1.19	1.26	1.42	0.77	0.79	1.07
Reductions in annual atrazine losses (%)	49	51	39	64	67	65	18	18	13
Pre-BMP atrazine losses, 10% POE (ppb/yr)	15.20	18.53	18.68	11.59	11.66	12.85	3.83	4.17	4.72
Post-BMP (incorporation) losses, 10% POE (ppb/yr)	4.11	3.89	4.65	2.44	2.39	2.51	1.61	1.61	1.73
Reductions in annual atrazine losses (%)	73	79	75	79	80	80	58	61	63

[a] Corn-soybean.

[b] Corn-corn-soybean.

[c] Continuous corn.

[d] POE=probability of exceedence.

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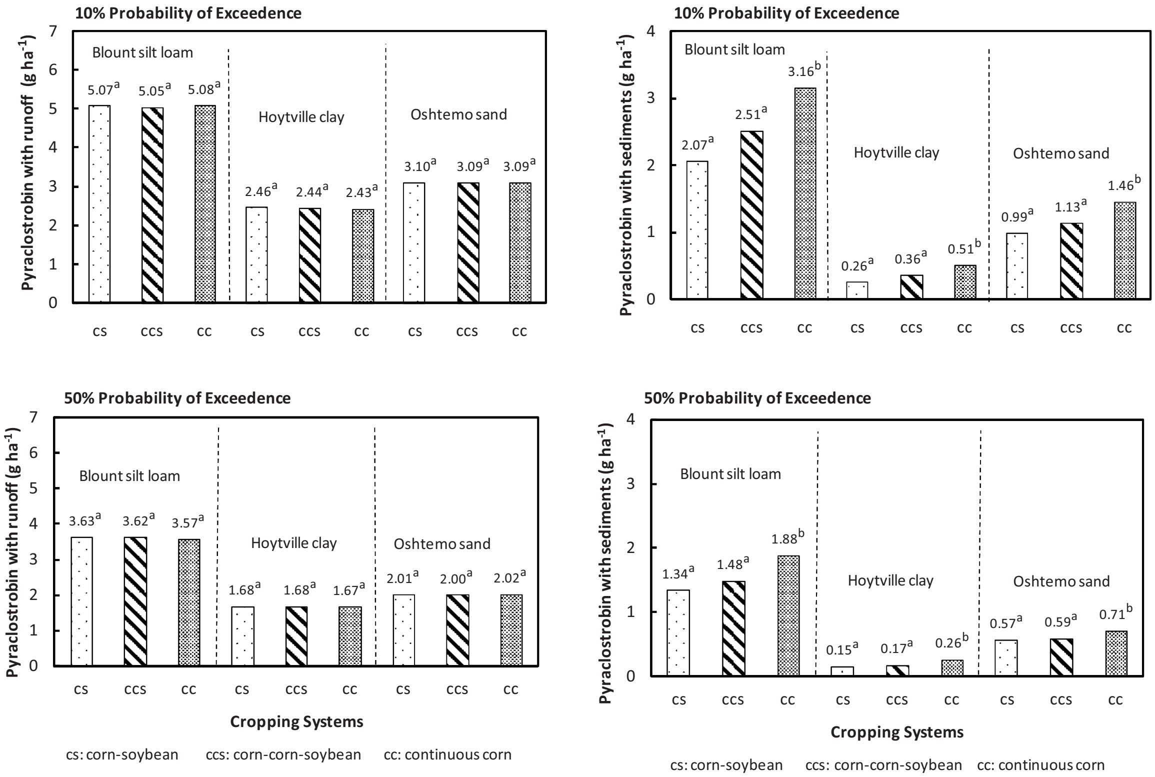

Fig. 9. Annual estimates in pyraclostrobin losses with runoff and sediments based on an application rate of 0.22 kg a.i. ha^{-1}. Within each soil, values followed by the same letter are not significantly different at the 5% level.

transport pathway as soil applied pesticides (Himel et al. 1990; Leonard et al. 1987). The primary transport process of organic pesticides, such as pyraclostrobin, from foliage or plant canopy to soil surface occurs mainly during rainfall events (Himel et al. 1990). Unless soils are initially wet, foliar pesticide residues are dislodged to the soil surface prior to runoff causing highly mobile compounds to move below the runoff zone (Wauchope et al. 2002; Leonard et al. 1987). Pyraclostrobin is not highly mobile, as indicated by a high K_{oc} value (11,000), suggesting that dislodged or washoff chemical from crop canopy would sorb to surface soils causing it to remain within the runoff zone (Wauchope et al. 2002; Sukop and Cogger 1992; Leonard et al. 1987). Since pyraclostrobin strongly adsorbs to soil particles, it will have a relatively lower risk to leaching below the root zone to contaminate ground water (Wauchope et al. 2002). A foliar washoff algorithm within the GLEAMS model relates washoff to rainfall volume and pesticide solubility and as such accounts for the above-ground pesticide dislodgement and partition (Leonard et al. 1987). This suggests that the modeling approach provides an accurate description of the environmental fate transport of pyraclostrobin used with corn production.

There were no statistical differences ($p < 0.05$) in annual losses of pyraclostrobin associated with surface runoff; however, mean annual losses of pyraclostrobin with sediments from continuous corn were significantly greater ($p > 0.05$) than corn-soybean and corn-corn-soybean rotation, possibly due to greater erosion losses under continuous corn production compared to other crop rotations (Fig. 4). Because pyraclostrobin has relatively greater affinity to soil, management practices will be needed to minimize erosion from agricultural fields to reduce fungicide losses. Without such practices, pyraclostrobin losses can be expected to increase, especially when corn stover is removed leaving agricultural fields more susceptible to erosion. Increasing demands for biofuels could result in increased usage of pesticides and increase water quality degradation from losses of these pesticides.

Conclusions

A shift from the current corn-soybean rotation to increased corn production was evaluated by considering two cropping systems: 2 years of corn production followed by 1 year of soybean rotation and continuous corn. A modeling approach was used to quantify annual losses in runoff, percolation, erosion, nitrates, total phosphorus, atrazine, and pyraclostrobin to the edge-of-field and bottom-of-root zones associated with multiple cropping scenarios. The quantified estimates provided insights to the posed question: What are the unintended consequences to water quality due to large-scale biomass production? The following conclusions can be made based on the results obtained in this study:

1. The results showed that agricultural management decisions involving shift to continuous corn cropping would greatly impact percolation, erosion, nutrients, and pesticides losses from agricultural fields and could potentially have greater impacts on runoff losses of those pollutants compared with the projected changes in crop rotations alone.
2. Cropping systems influenced available soil residue, which would affect infiltration, surface runoff, and percolation. Soil loss is an important component in understanding biofuel production impacts on the environment because persistent agrochemicals often attach to soil particles.
3. The model results suggest that CRP acres returned to con-

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tinuous corn would experience significantly higher erosion losses to the edge-of-field; thereby, creating potentially negative water quality impacts from sediments and particle bound pollutants. In worst- and average-case scenarios, continuous corn, which employed conventional tillage, resulted in significantly greater ($p > 0.05$) losses in mean annual erosion losses when compared with corn rotation systems. Estimated annual erosion losses on CRP lands were projected to be greater than worst-case 7.50 t/ha and average-case 4.30 t/ha experienced on Blount silt loam due to greater slopes, *K*-factor values, soil texture differences, and bulk density.

4. Nutrient loss results imply that cropping system shifts due to increased corn production for corn-based ethanol would result in higher estimates in nitrate-N and TP losses. If the push to corn-ethanol continues, agricultural producers would apply greater amounts of commercial fertilizer resulting in greater nitrate-N and TP losses.
5. Best management practices, such as atrazine incorporation, rather than shifts in cropping systems, could reduce annual atrazine losses (surface water concentration) from agricultural fields by as much as 58–80%.
6. Increasing demands for biofuel could result in increased usage of fungicides such as foliar pyraclostrobin to increase corn yields. Although there were no statistical differences ($p < 0.05$) in annual losses of pyraclostrobin with surface runoff, mean annual losses of pyraclostrobin with sediments from continuous corn were significantly greater ($p > 0.05$) than corn-soybean and corn-corn-soybean rotation.

The push to ethanol to meet transportation fuel demands could create a land management practice that focuses on yield increase while showing little or no regards for environmental consequences. Nonetheless, various management practices could reduce some of the negative consequences associated with the increased corn production to meet biofuel demand; these practices need to be carefully evaluated and implemented. The grand challenge to U.S. energy security is to determine suitable, stable, and efficient feedstocks for the production of ethanol in the United States. To address the sustainability of U.S. biofuel production, it will be essential to include scientific assessment of environmental issues, not limited to greenhouse gas emissions.

Acknowledgments

The writers wish to thank Leighanne Hahn of the Office of Indiana State Chemist for pesticide related information; Chetan Maringanti and Dr. Tong Zhai for support with this project. Suggestions provided by two anonymous reviewers greatly improved an earlier version of this manuscript.

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