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Examining the impacts of increased corn production on groundwater quality using a coupled modeling system

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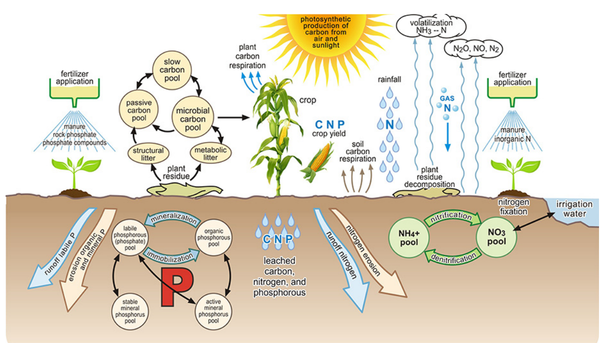
HIGHLIGHTS

- Corn ethanol demands can increase corn production in 2022.
- Nitrogen (N) from fertilizer can leach into groundwater causing health impacts.
- Coupled models were used to regress on measurements and project increased corn production impacts.
- The *rate* of N fertilizer placed on *irrigated grain* corn was the strongest N-loading predictor.
- Our scenario resulted in a 56%–79% increase in areas with high groundwater nitrate.

GRAPHICAL ABSTRACT



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ABSTRACT

This study demonstrates the value of a coupled chemical transport modeling system for investigating groundwater nitrate contamination responses associated with nitrogen (N) fertilizer application and increased corn production. The coupled Community Multiscale Air Quality Bidirectional and Environmental Policy Integrated Climate modeling system incorporates agricultural management practices and N exchange processes between the soil and atmosphere to estimate levels of N that may volatilize into the atmosphere, re-deposit, and seep or flow into surface and groundwater. Simulated values from this modeling system were used in a land-use regression model to examine associations between groundwater nitrate-N measurements and a suite of factors related to N fertilizer and groundwater nitrate contamination. Multi-variable modeling analysis revealed that the N-fertilizer *rate* (versus total) applied to *irrigated* (versus rainfed) *grain corn* (versus other crops) was the strongest N-related predictor variable of groundwater nitrate-N concentrations. Application of this multi-variable model considered groundwater nitrate-N concentration responses under two corn production scenarios. Findings suggest that increased corn production between 2002 and 2022 could result in 56% to 79% increase in areas vulnerable to groundwater nitrate-N concentrations ≥5 mg/L. These above-threshold areas occur on soils with a hydraulic conductivity 13% higher than the rest of the domain. Additionally, the average number of animal feeding operations (AFOs) for these areas was nearly 5 times higher, and the mean N-fertilizer rate was 4 times

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higher. Finally, we found that areas prone to high groundwater nitrate-N concentrations attributable to the expansion scenario did not occur in new grid cells of irrigated grain-corn croplands, but were clustered around areas of existing corn crops. This application demonstrates the value of the coupled modeling system in developing spatially refined multi-variable models to provide information for geographic locations lacking complete observational data; and in projecting possible groundwater nitrate-N concentration outcomes under alternative future crop production scenarios.

1. Introduction

Nitrogen (N) is critical to life on earth, but excess N can be transported to waterways in surface and subsurface runoff, leached into groundwater or emitted to the air and deposited back to underlying surfaces. Exposure to this excess N can result in ecological and human health impacts such as fish kills, human disease and birth defects (Johnson et al., 2010; Ward et al., 2005). Agricultural activities are a significant source of N released into the environment by humans. Corn production, in particular, requires large amounts of N fertilization to achieve the highest yields (Ribaudo et al., 2011; Sobota et al., 2013). Demand for corn grown in the United States (US) is expected to rise because corn is an important commodity for sustaining world populations, and more recently, because of its use as a biofuel. This increase in demand for corn, and subsequent increase in N fertilization, may raise the risk of human exposures to nitrate from contaminated drinking water wells. Exposure through the consumption of contaminated drinking water has been associated with some cancers and birth defects (Ward et al., 2005; Brender et al., 2013).

The rising demand for corn in the US, however, is also expected to be met with technology advancements, cropland redistributions, and a vegetation-enhancing atmosphere higher in carbon dioxide levels (Lark et al., 2015; The Hightower Report, 2015). The ability to anticipate the opposing impacts of evolving political (e.g., agricultural subsidies, biofuel production mandates), economic (e.g., demand for food and livestock feed) and environmental (e.g., weather, soil health) conditions is essential to understanding the intended and unintended consequences of current and future demand for corn. Integrated or coupled systems-level modeling has the potential to provide the spatially complete, detailed information needed to develop exposure models that meet these emerging demands, while providing improved (refined) identification of locations that would benefit from more rigorous, resource-intensive analyses. In addition, such models are needed to examine the impact of environmental decisions through future scenario analyses.

In this study, we used a coupled modeling system to simulate the impacts of various corn production scenarios. We used consistent inputs (e.g., emissions, meteorology, land use) to drive the component models within the coupled modeling system, and maintained mass-balanced equations throughout the integrated simulations, resulting in a rich source of information on the fate of N originating from crop fertilization. We used this extensive dataset in a statistical model to describe N-loadings to groundwater as a function of a variety of environmental variables. These variables included measurements of nitrate-N in drinking water wells from the US Geological Survey (USGS), and data from the coupled model at those well locations, to estimate nitrate-N in groundwater at all other locations that met our model criteria but lacked well water observations. With this approach, we estimated N loadings and related groundwater nitrate-N concentrations for 2002 (before the introduction of new US biofuel policies) and two future-year simulations (2022_{BASE}, increasing population demand and increasing CO_2 concentrations; 2022_{CROP}, and hypothetical biofuel production targets in addition to 2022_{BASE} production increases).

While several other generalizable studies (e.g., DeSimone et al., 2009; Nolan et al., 2002; Greene et al., 2005; Nolan and Hitt, 2006) have revealed associations between N-loadings from agricultural management practices (e.g., proximity of animal feeding operations, total amount of inorganic N fertilizer) and groundwater nitrate contamination, these studies were limited by their reliance on historical county level fertilizer sales data, which in turn, are tied to social policies, economic constraints, and spatially incomplete management and weather conditions. Our approach provides more physically and spatially detailed N loading information (e.g., type of fertilizer placed on each crop type, use of drainage tiles, tillage, or irrigation). This allowed us to provide more geographically targeted outcomes, which are of use in fine-tuning future data collection for specific areas, and improving the characterization of wellhead rotation and auger recharge areas. More detailed, process-based characterization of fertilizer applications also allowed us to examine the impact, both collectively and by individual driver, of corn production scenarios on groundwater nitrate-N contamination under environmental and socio-economic conditions that transcend the historical conditions. Accordingly, the objectives of this study are to: (1) refine our understanding of N loadings and interactions related to crop fertilization and groundwater nitrate contamination; (2) predict changes in groundwater nitrate contamination for a base- and two future-year agricultural corn production scenarios; and (3) examine these changes to better understand the impacts of potential corn production expansion on groundwater quality.

2. Approach

The US Environmental Protection Agency's (EPA's) CMAQ version 5.1 model with bidirectional ammonia exchange (bidiCMAQ) was coupled with a modified version of the US Department of Agriculture's (USDA's) Environmental Policy Integrated Climate (EPIC; Williams et al., 2012) agroecosystem model as described in Cooter et al. (2012) and Bash et al. (2013). BidiCMAQ employs a 3-dimensional Eulerian modeling approach to address regional air quality issues such as tropospheric ozone, fine particles, acid deposition and visibility degradation (Appel et al., 2011). EPIC is a field-scale, semi-empirical model that produces daily estimates of fertilizer applied to all crop types grown in the US. More information about how these models were coupled and the related model evaluation can be found in Cooter et al. (2012) and Bash et al. (2013). While the coupled modeling system does not provide estimates of groundwater nitrate-N directly, it does simulate the movement of reactive N through the soil layers. We used the 2002 annually summed or averaged N-loading variables produced by the bidiCMAQ-EPIC modeling system (e.g., N deposition, N fertilizer applied, N soil concentrations, and agriculture management practices such as tilling and irrigation) in a land-use regression model, using nitrate-N measurements taken by USGS in 2002 from drinking water wells located predominantly in agricultural areas throughout the US (Fig. 1a) as the response variable. We then applied the coefficients calculated from the land-use regression approach to predict groundwater nitrate-N concentrations for 2002 throughout the remaining U.S. domain and for two crop production scenarios in 2022. Two policy drivers are included in our scenario analysis; the adoption of hypothetical corn-based biofuel (ethanol) production volumes and the implementation of prescribed Clean Air Act (CAA) emission reductions (http://www.epa.gov/criteria-air-pollutants/naaqs-table/). Our scenarios analysis begins in 2002 to simulate conditions prior to the active implementation of both these policies, and ends in 2022 when ethanol production