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Nitrogen balance in Iowa and the implications of corn-stover harvesting

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ABSTRACT

Increased corn production and removal of corn stover for biofuel production can adversely affect water quality, soil fertility and productivity due to low nitrogen (N) use efficiency. In this study, the average annual county-level N balances in Iowa are calculated for three corn-involved rotations: corn-soybean (C-S), corn-corn-soybean (C-C-S) and continuous corn (C-C), receiving either synthetic-N or manure fertilizer under 0, 30, 50 and 75% corn stover removal scenarios. Geo-referenced data on soil, crop and livestock are used to estimate net changes in total N balance in the mineral form after accounting all soil N inflows and outflows. Under a zero stover removal scenario, a state average for net N was 34 kg ha^{-1} yr^{-1}. Approximately 86% of the land area in the three corn-involved rotations receives synthetic-N fertilizer, and 24% of total synthetic-N treated land is estimated with net N of 24 kg ha^{-1} yr^{-1} (i.e., average net N for synthetic-N treated rotations) or more. Manure-treated rotations are estimated to have 2–6 times higher net N than synthetic-N treated rotations; continuous corn rotations contributing to a higher net N. The northern and central crop districts dominated by animal and corn production have higher net N. Removal of corn stover reduces net N, and synthetic-N treated rotations are estimated to be affected the most. The percentage of total synthetic-N treated rotations estimated with net N of 24 kg ha^{-1} yr^{-1} or more lowers from 24% under no stover harvesting to 3% under 75% stover (mass basis) removal scenario. Conversely, the areas with negative net N increase from 1% with no stover harvesting to 10% under 75% harvesting. This study will help prioritize the regions in which management practices that reduce nitrogen loss are most needed, and those regions most suitable from a nutrient balance standpoint for sustainable stover harvesting.

1. Introduction

Row crop production and animal feeding operations are the major contributors of plant nutrients, particularly nitrogen (N) and phosphorus (P), exported from the Mississippi River to the Gulf of Mexico (David et al., 2010; Alexander et al., 2007; Goolsby et al., 1999). Increased concentration of these nutrients in the northern Gulf of Mexico has increased the size of the Gulf hypoxic zone which has averaged over 15,600 km^2 since 1993, making it one of the largest hypoxic zones in the world (Rabalais et al., 2002). Depletion of valuable fisheries and the disruption of ecosystem services are economic and ecological consequences of hypoxic zones. Donner and Scavia (2007) suggested a 50–60% N load reduction is necessary to reach the Gulf hypoxia area goal (i.e., 5-year running average hypoxic zone < 5000 km^2) laid out in the Hypoxia Action Plan. Nutrient loss from agricultural land also has human health impacts. Long-term exposure to nitrate (NO_3^-) in drinking water derived from impacted water sources increases the risk of cancer in humans (Weyer et al., 2001). The concentration of NO_3-N in agricultural drainage often exceeds the drinking water standard of 10 mg NO_3^--N/L and annual NO_3^- loadings from farms in the Midwestern region of U.S. are often over 66 kg NO_3^--N ha^{-1} (Kalita et al., 2006).

It is expected that the implementation of the revised Renewable Fuel Standard (RFS2) will put more land in the Mississippi River Basin into agricultural production either through the transformation of uncultivated pasture and conservation reserve program (CRP) lands or conversion of other cropping systems to more corn-involved systems (Marshall et al., 2011). In turn, nutrient transport from the basin is expected to increase, further compromising the

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hypoxic zone reduction goal (Donner and Kucharik, 2008). Higher corn production would also make it more difficult to meet the total maximum daily load limits (TMDL) under the Clean Water Act (EPA, 2012) resulting in additional water bodies not meeting water quality standards. The RFS2 mandates by 2022 the annual production of 56.8 and 60.5 billion liters (i.e., 15 and 16 billion gallons) of corn-grain and ligno-cellulose based ethanol, respectively. Corn stover, the residues left in fields after corn grain harvest, has been targeted as a readily available feedstock for cellulosic ethanol production (Perlack et al., 2005). Corn stover harvesting has the potential to reduce soil drainage N concentration compared to no stover harvesting in corn-involved cropping systems (Zavattaro et al., 2012; Meki et al., 2011). The decision to harvest stover should be considered carefully as it also has the potential to decrease soil organic carbon (SOC); reduce soil microbial activity; increase soil susceptibility to compaction, runoff, and soil erosion; reduce nutrient pools, water retention, and soil fertility, and hence soil productivity and crop yield (Zavattaro et al., 2012; Blanco-Canqui, 2010; Karlen et al., 2009; Graham et al., 2007; Grignani et al., 2007; Andrew, 2006; Wilhelm et al., 2007).

Iowa is the largest corn, soybean and hog producing state in the U.S. (NASS, 2012). A large fraction of the total land area is planted with corn and soybean (39 and 26%, respectively). Also, there is a high geographical concentration of large and specialized confined animal feeding operations (CAFOs), the vast majority producing hogs. Most animal waste is disposed through land application. Large CAFOs typically own less land than would be required to use the manure they produce agronomically on their own fields. Recent increases in the number and size of CAFOs have raised environmental concerns related to over-application of manure and leaching of excess nutrients from the fields to surrounding water resources. During the flood year of 1993, Iowa was estimated to contribute about 35% of the total nitrate discharged to the Gulf of Mexico although it represents only 4.5% of the total land area of Mississippi-Atchafalaya River Basin (Goolsby et al., 1999). Based on water quality monitoring data, water in the majority of Iowa streams during 2000–2012 was classified as "poor" quality (IDNR, 2013).

The nutrient balance is often used as an indicator of a system's ability to maintain soil fertility as well as water quality in adjacent ecosystems (Grignani et al., 2007). Nutrients in excess of crop requirements are prone to leaching while nutrients in deficit of crop requirements reduce soil fertility, which in turn lowers crop productivity. Quantifying the nutrient balance of corn-involved crop rotations under different fertilizer and residue management practices can help us to develop effective policies addressing nutrient-related environmental problems, and achieve sustainable corn stover harvest for biofuel production. The objectives of this study are to examine the spatial distribution of N balance under different corn-based cropping systems, manure management systems and corn stover harvesting scenarios in Iowa.

A county level N balance model that links the stocks and flows of N in crops, animals, and soil is developed to estimate the N balance in three major corn-involved crop rotations (i.e., corn-soybean (C-S), corn-corn-soybean (C-C-S) and continuous-corn (C-C)), under two fertilizers (i.e., manure and synthetic-N), and with 0, 30, 50 and 75% corn stover removal. Traditionally, a limited amount of corn stover has been harvested for animal feed and bedding, with a substantial portion of the residues being returned to the soil (Karlen et al., 2011). It is assumed that all of the stover residues are left on the ground, and we consider 0% stover harvesting as the "business as usual (BAU)" scenario. The model in this study follows the approach used in previous studies (Burkart et al., 2005, 2006). Burkart et al. (2005) examined leachable N under alternative land use scenarios that considered an increase in land areas under perennial cover, integrated livestock with cropping systems, and reduced use of inorganic fertilizer in western Iowa watersheds. In contrast to the work of Burkart et al. (2005), the model developed here is used to estimate leachable mineral N and soil organic N at near steady-state conditions.

Compared to existing models, such as EPIC (Williams et al., 1984), DAYCENT (Del Grosso et al., 2001), DNDC (Li et al., 1992), and Agro-IBIS (Kucharik, 2003; Kucharik et al., 2000), the model used in this study is simple, needs fewer and more accessible inputs, and captures major N dynamics in the agricultural systems at county and watershed scales. This model includes physical processes, such as loss of ammonia (NH_4) during plant senescence and redeposition of locally derived NH_4, which are generally ignored in detailed process-based models (Burkart et al., 2005).

The N balance in this study is reported as net mineral N. "Net N" is the difference between total inflows and outflows of N in the soil system. Positive net N (i.e., surplus N) indicates that the system has N inflows in excess of outflows, and surplus N has a potential to leave agricultural fields through leaching or runoff during wet years. Negative net N (i.e., deficit N) indicates a system with higher N outflows than inflows. Such a system is losing N over time and will eventually require additional N to maintain ecosystem function and crop productivity.

2. Methodology

2.1. Study area

Our study area, the state of Iowa, is located in the north-central part of the United States (Fig. 1); it is a core part of the Western Corn Belt Plains Ecoregion (Omernik, 1987). Soils in the central and northern regions have relatively lower clay content, higher bulk density, and higher SOC stock levels than other parts of the state. Average annual precipitation varies from 710 mm in the northeast to 965 mm in the southwest, and average annual minimum temperature is 0.5 °C in the northeast and 6.1 °C in the southwest. Cropland accounts for more than 85% of the state, and the major crops, corn and soybean, dominate the landscape. Figs. S2 and S3 in the supporting material (SI) provide county level information about the distribution of various cropping systems, animals and fertilizer management practices in Iowa.

2.2. N model

Soil nitrogen, both inorganic and organic (i.e., mobile and immobile forms of N), is influenced by the addition of crop residues, livestock manure and atmospherically deposited nutrients. Soil organic nitrogen (SON) is not directly available to plants, and is protected from loss via leaching, whereas mineral N is available for a crop to uptake, and can leave the system through runoff or leaching during wet seasons. The N model developed in this study represents organic N dynamics through the inclusion of three soil organic pools, which are regulated through the mineralization and immobilization processes (Burkart et al., 2005), as shown in Fig. 2. The system N balance is calculated as:

$$\text{Net N} = \text{Fert} + M_{\text{m}} + M_{\text{r}} + M_{\text{son}} + \text{Fix} + Atm - \text{CropU} - \text{FertVol} - \text{CropV} - \text{Deni} \quad (1)$$

where Net N is total N in the mineral form after accounting all soil N inflows and outflows, M_{m} is fertilizer application, M_{r} is mineralized manure, Fert is mineralized residue, $M_{\text{son}}$is the contribution of mineralized N from three soil organic pools (i.e., Active, Slow and Passive), Fix is atmospheric N fixation, Atm is atmospheric N deposition (wet and dry), CropU is crop uptake, FertVol is fertilizer application loss via volatilization, CropV is ammonia volatilization