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Dynamic model-based recommendations increase the precision and sustainability of N fertilization in midwestern US maize production

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ABSTRACT

The US Midwest encompasses one of the largest intensive maize (*Zea mays* L.) production environments in the world. Managing these lands in a more sustainable way is essential to reducing environmental stresses. This study explores the potential of Adapt-N, a dynamic biogeochemical model, to more precisely manage N inputs compared to a static N management approach, the Maximum Return to N (MRTN). Data from 16 multiple N rate trials conducted over two years (2013–2014) in three Midwest states were used to reconstruct two yield response functions: quadratic (QD) and linear-plateau (LP), allowing estimation of the Economic Optimal N Rate (EONR), and yields resulting from Adapt-N and MRTN recommendations. Model-based N rates were better correlated with the EONR based on the LP function, and were similar based on the QD function. Applying a dynamic approach to N recommendations allowed a significant reduction in applied N (averaging 28 kg ha^{-1}; 13%) without compromising yield, thereby maintaining farmer's profits while reducing simulated environmental N losses. Longer-term simulations showed that the largest reductions in N rates by Adapt-N compared to the MRTN occurred in dry seasons when early season N losses were small. This study shows that model-based N recommendations can have both economic and environmental benefits compared to a static N management approach.

1. Introduction

Managing agricultural systems more sustainably is a major current global challenge (Garnett et al., 2013; Godfray et al., 2010; Lipper et al., 2014; Tilman et al., 2011; Zhang et al., 2015). The global consumption of fertilizer-N has increased in the last few decades to allow greater crop production and accommodate the growing world population and food demand (Erisman et al., 2008). However, increased fertilizer consumption is often associated with low N Use Efficiency (NUE – the ratio of N removed by crop products to the field N input, Zhang et al., 2015), indicating that a large proportion of applied N is lost from agricultural fields into the environment. Such N losses have a substantial cost to society across multiple facets (Sobota et al., 2015; van Grinsven et al., 2015), including nitrate (NO_3) losses below the root zone that readily contaminate ground water, surface water, and estuaries (David et al., 2010; Diaz and Rosenberg, 2008; Gu et al., 2013), and nitrous oxide (N_2O) losses that pose significant greenhouse gas concerns (Smith et al., 2008). These contribute to human and ecosystem health issues (Johnson et al., 2010; Keeler et al., 2016; Thurber et al., 2014; Townsend et al., 2003).

In the US, maize is the single largest consumer of N fertilizer (157 kg ha^{-1} on average, USDA ERS, 2013). NUE of maize crops in the US is often relatively low (0.37; Cassman et al., 2002), indicating that a large amount of N is lost to the environment in these agricultural production environments. The Mississippi River Basin is home to a large intensive row crop production region, the Midwest Corn Belt, encompassing 85% of all US maize production (USDA ERS, 2016). Excess nutrients from agricultural fields are transported down the Mississippi River, risking water resources and contributing to an extensive annual hypoxia zone in the Gulf of Mexico (Rabalais et al., 2002, 2007). Despite major efforts in nutrient management planning, reducing nutrient loading into the Gulf and shrinking the hypoxia zone has proven to be very challenging, with the 2017 hypoxia zone the largest ever recorded (NOAA, 2017a).

One solution to the problem of excess nutrients is to better synchronize applied N with crop N demand and eliminate excessive N applications. However, determining the right N rate for a specific field is challenging as soil N availability is affected by multiple interacting

Abbreviations: QD, quadratic; LP, linear-plateau; EONR, Economic Optimal N Rate; MRTN, Maximum Return to N

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factors such as weather (Kahabka et al., 2004; Xie et al., 2013), soil type (Shahandeh et al., 2005), and soil organic matter levels (Mulvaney et al., 2001). In addition, the timing (McLellan et al., 2018), formulation (Abalos et al., 2014; Halvorson et al., 2014), and placement of N fertilizer (Nkebiwe et al., 2016), as well as rotations, cover crops (Melkonian et al., 2017), use of stabilizers, etc. affect N losses and soil N availability, and hence the N rate needed to secure season long crop N requirements. Therefore, the optimal N rate needed to reach a specific target yield is expected to vary spatially among fields, and temporally for the same field. The uncertainty associated with the proper N rate for a specific field, together with low fertilizer prices relative to high revenues from crop yields, lead many farmers to apply excessive fertilizer (Dobermann and Cassman, 2004) to ensure the crop growth is not limited by N availability.

Several tools have been developed that generate suitable N recommendations for grower fields (Morris et al., 2018). These can be classified as static or adaptive. An example of a static approach is the Maximum Return to N (MRTN; Sawyer et al., 2006), an empirical approach promoted in the US Corn Belt by university extension services. This method utilizes datasets of multiple N rate trials where the relationship between N rate and yield was quantified via an N-response curve, allowing for the estimation of the most profitable N rate. While using an average, static N rate might ease implementation by growers, this approach does not account for highly variable production environments or the seasonal dynamics of soil N. The MRTN guidelines acknowledge that the method cannot predict site-specific N requirements (Sawyer et al., 2006) and, in some cases, the guidelines point to other tools such as soil tests or canopy sensors to fine-tune field N management (Camberato and Nielsen, 2017).

Adaptive N recommendation tools for maize include soil tests (e.g., the Pre-Sidedress Nitrogen Test; Magdoff et al., 1984), or more dynamic tools such as crop canopy N sensors (Kitchen et al., 2010; Scharf et al., 2011), and physically-based models such as Adapt-N (Melkonian et al., 2008; Sela et al., 2016), Maize-N (Setiyono et al., 2011), or APSIM (Holzworth et al., 2014). Model-based N recommendation tools are appealing as they are highly scalable and can be coupled with site-specific weather data and field management conditions (e.g., yield expectation, tillage, crop hybrid and data regarding residual N) to generate highly space and time-specific N recommendations. For split N management, where the bulk of N is applied in-season, Thompson et al. (2015) found model-based N recommendations to be comparable with in-season N recommendations derived from crop canopy sensors for sites in MO, NE and ND. The Adapt-N tool was recently found to perform favorably over the grower regular practice in strip trials conducted in Iowa and New York (Sela et al., 2016), allowing for a significant reduction in N application without yield loss. In another study, Adapt-N better predicted the Economic Optimum N Rate (EONR) while reducing environmental losses when compared with a static N recommendation tool in multiple N rate trials conducted in NY (Sela et al., 2017). A dynamic model-based approach allows flexibility in adjusting N rates depending on interactions of site-specific seasonal weather conditions with soil, crop and management factors (Sela et al., 2016, 2017). Therefore under drier circumstances, where weather-induced N losses are minimal, a model-based approach will recommend lower N than under wetter conditions. In contrast, static N recommendations do not account for seasonal weather. There is a need to understand how dynamic N rates adjust to account for different weather, soil and management conditions, and how they compare to a static approach. This is addressed here using a dataset of multiple N rate trials conducted in three Midwestern states – IN, OH and WI – during the 2013–2014 growing seasons using Adapt-N as an example of a dynamic model-based tool and the MRTN approach as a conventional static method. The hypothesis for this study was that the dynamic approach allows grower profits to be maintained while N application rates and related environmental effects are appreciably reduced.

2. Materials and methods

2.1. Maximum Return to N (MRTN)

The MRTN approach (Sawyer et al., 2006) relies on a large dataset of field trials where multiple N rates and the corresponding yields were used to generate grain yield to fertilizer response curves. For each state (and in some states different regions or soil types), the recommended N rate is based on an average (multi-year and site) yield response curve, from which the largest average net return is identified. Recommendations can vary with grain-to-fertilizer price ratio or according to the crop rotation. The method allows for the calculation of a range of N rates that are expected to result in a profitable yield. For this study, MRTN rates were determined from an on-line calculator http://cnrc.agron.iastate.edu/, based on a maize grain price of \$0.197 kg^{-1} (\$5 bu^{-1}) and N fertilizer price of \$1.098 kg^{-1} (\$0.5 lbs^{-1}) – average values for the period 2007–2013 (USDA NASS, 2015; USDA ERS, 2015). In all trials, the in-season sidedress N recommendation by the MRTN approach was calculated as the total N recommended minus any N applied prior to sidedress time, i.e., preplant or starter.

2.2. Adapt-N

A detailed description of the Adapt-N tool and input data needed to run a simulation is provided in Table A.1 (Sela et al., 2016). Adapt-N is a web-based tool accessible through internet-connected devices that support web browsers. The tool uses high resolution daily weather data (4 × 4 km), available in near real-time (6 h lag). Relevant climate data, such as precipitation and temperature, are derived from routines using the US National Oceanic & Atmospheric Administration's Rapid Update Cycle (NOAA RUC) weather model and operational Doppler radars. The engine of the Adapt-N tool is the Precision Nitrogen Management (PNM) model (Melkonian et al., 2002), an integration of the LEACHN biogeochemical model (Hutson, 2010) with a crop growth model (Sinclair and Muchow, 1995). The result is a 1-D biogeochemical model that simulates soil hydrology, N fluxes through the soil-plant-atmosphere continuum, as well as plant N uptake and growth on a daily time step. The model accounts for mineralization of organic matter and the immobilization of N by the microbial biomass as a function of C and N flows into the biomass pool. The model also accounts for the effect of soil moisture and temperature on N transformation rates and estimates soil N, crop N uptake, atmospheric gaseous N losses, and nitrate leaching below the root zone. The LEACHN model was extensively validated in previous studies (e.g., Jabro et al., 1995, Jabro et al., 2006; Sogbedji et al., 2001a,b). The PNM model was successfully validated in previous studies in different production environments, with good agreement between simulated results and observed water drainage, nitrate leachate, soil inorganic N and crop N uptake (Marjerison et al., 2016; Melkonian et al., 2017; Sogbedji et al., 2006).

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.compag.2018.08.010.

The Adapt-N tool utilizes data from the PNM model to generate near real-time N recommendations by solving a dynamic mass balance equation on a daily basis (all units in kg ha^{-1}):

$$N_{rec} = N_{exp\_yld} - N_{crop\_now} - N_{soil\_now} - N_{rot\_credit} - N_{fut\_gain\_loss} - N_{profit\_risk} \quad (1)$$

where N_{rec} is the N rate recommendation; N_{exp_yld} is the total crop N quantity needed to achieve the expected (potential) yield, a value supplied by the user for each field or zone; N_{crop_now} and N_{soil_now} are the N quantity in the crop and the inorganic N quantity in the soil as simulated by the PNM model for the current simulation date accounting for previous N applications; N_{rot_credit} is a partial N credit from crop rotation (e.g. soybean crop); $N_{fut\_gain\text{-}loss}$ is a probabilistic estimate of future N gains from organic N mineralization minus losses until the end of the growing season, based on model simulations with historical rainfall distribution functions; and N_{profit_risk} is an economic adjustment