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Using the Adapt-N model to inform policies promoting the sustainability of US maize production

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Abstract. *Maize (Zea mays L.) production accounts for the largest share of crop land area in the U.S. It is the largest consumer of nitrogen (N) fertilizers but has low N Recovery Efficiency (NRE, the proportion of applied N taken up by the crop). This has resulted in well-documented environmental problems and social costs associated with high reactive N losses associated with maize production. There is a potential to reduce these costs through precision management, i.e., better application timing, use of enhanced efficiency products, and more precise rate calculations. However, promoting management changes by means of environmental policies requires robust analysis of the possible environmental outcomes. This research gap is addressed using Adapt-N, a computational precision N management tool that combines soil, crop and management information with near-real-time weather data to estimate optimum N application rates for maize. Using results from a large synthetic dataset of 8100 simulations spanning 6 years (2010-2015), we have explored the total required N rates and environmental losses resulting from seven N management scenarios applied in the top 5 US maize production states – IL, IN, IA, MN and NE. To cover a wide range of weather and production environments, all scenarios were applied at five randomly selected locations in each state, using combinations of three soil texture classes and two organic matter contents. The results indicate that fall applications lead to the lowest NRE with substantial amounts of N losses and highest total amount of required N. Nitrification inhibitors were found to have marginal benefits for fall applied N, but effective with spring applications. Spring pre-plant N applications where found to have higher NRE than fall applications, but could still lead to high N losses under wet spring conditions. These losses were significantly reduced when nitrification and urease inhibitors were applied. Out of all simulated N management scenarios, applying a split application of a modest* *starter followed by the majority of N applied at sidedress was found to have on average the lowest total N amount required, lowest N losses and overall, and highest NRE. These results demonstrate that computational precision management tools could be used to inform environmental policies and business models to reduce environmental costs associated with maize production in the U.S.*

Keywords. *Maize; Crop simulation tool; N management;*

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1. Introduction

Maize [Zea mays L.] accounts for 27% of the US crop land area (USDA NASS, 2015) and receives on average the highest N rate among major field crops (157 kg ha-1; USDA-ERS, 2015a). Maize N management in the US is often relatively inefficient, with N Recovery Efficiency (NRE, the proportion of applied N taken up by the crop) estimated at 37% (Cassman et al. 2002), but can be as high as 67% for split N applications on irrigated maize (Wortmann et al. 2011). Application of N fertilizer use in excess of crop demand can have an adverse, well documented effect on the environment (Gruber and Galloway 2008; Vitousek et al. 1997). Nitrate leaching can affect groundwater aquifers (Böhlke 2002; Gu et al. 2013) and aquatic biota in downstream streams and estuaries (Carpenter et al. 1998; Diaz and Rosenberg 2008). Nitrogen losses through denitrification can result in increased emissions of nitrous oxide (N_2O; (McSwiney and Robertson 2005)), a potent greenhouse gas for which agriculture is the main anthropogenic source (Smith et al. 2008). Altogether, increased anthropogenic N fluxes into the environment have a significant economic cost for society (Dodds et al. 2009; Sutton et al. 2011).

One of the factors leading to excess agricultural N application and environmental N losses is that soil N is spatially and temporally variable (Kitchen et al. 2010; Scharf et al. 2005; van Es et al. 2007). Therefore, defining a location-specific economically optimum N rate (EONR, the N rate at which further increase in N is no longer economical) is challenging. The EONR is affected by multiple resource and production-related factors, including the timing and rate of precipitation events during the early growing season (Tremblay et al. 2012; van Es et al. 2007), N mineralization from soil organic matter (SOM), carry-over N from previous cropping seasons (Ferguson et al. 2002; Mulvaney et al. 2001), soil texture (Shahandeh et al. 2005), crop rotations (Stanger and Lauer 2008), topographic position affecting soil moisture availability (Schmidt et al. 2007; Zhu et al. 2015), organic carbon (Pennock 2005), and the timing of N application (Dinnes et al. 2002).

According to USDA data (USDA_ERS 2015b), on average 27% of US farmers apply some N as fall preplant application, 61% apply some N as a spring preplant application, and only 32% practice in-season (i.e., split) N applications. However these estimates vary from state to state (Table 1). Note that the percentages add up to more than 100%, as many farmers apply N to their fields more than once a year. The timing of N application has been suggested as a way to reduce N losses (Robertson and Vitousek 2009), although the environmental benefits of split application over large preplant applications are still under debate. Split N applications improve the synchronization of N availability with the crop N requirements, and therefore tend to reduce environmental N losses (van Es et al. 2006). However, other studies found split N applications to have no effect on N losses (Jaynes and Colvin 2006) or to even increase N losses when the sidedress is followed by large rainfall events (Venterea and Coulter 2015).

The application of enhanced efficiency fertilizers (EEF) has also been suggested as a way to reduce environmental losses. USDA data (Table 1) suggest a higher fraction of fields receiving EEF with increasing precipitation along a west-to-east gradient in the Midwest. However, the environmental efficiency of EEF is still under debate, as EEFs have been found to either decrease N losses (Halvorson and Del Grosso 2012; Halvorson et al. 2011, 2014) or to have no effect on N losses (Parkin and Hatfield 2014). Most studies, however, do not account for the fact that total N rates may be reduced with the use of EEF, which can be accounted for with precision computation N tools like Adapt-N. Altogether there is a need to further explore the aggregate effects of modifying the timing, form and rates of N application in combination with the use of computational precision N management on environmental N losses under different climatic regimes.

Table 1. Mean annual precipitation for each state for the period of 1990-2009 calculated using the PRISM model (National Atlas of the United States 2011), the percentage of fields in each state that receive N in different N application timing and the percentage of fields where fertilizer inhibitors are used (USDA_ERS 2015b). Note that the presented percentage sums to more than 100% as some growers apply N more than once each year.

State	NE	MN	IA	IL	IN
Annual precipitation (mm)	645	763	939	1103	1195
N applied in the fall (%)	12*	33	49	46	17*
N applied in the spring (%)	52	63	63	75	66
N applied at planting (%)	47	49	14	7*	38
N applied following planting (%)	51	8*	14	23	48
N inhibitor used (%)	3	8*	13*	28	44*

* Statistically unreliable due to a low sample size.

Adapt-N

Adapt-N is a web-based N recommendation tool for maize. It was developed by Cornell University and is now commercially available to farmers in the US (Adapt-N.com). It is based on the Precision Nitrogen Management (PNM) model (Melkonian et al. 2005), which in turn is an integrated combination of the LEACHN biogeochemistry model (Hutson and Wagenet 2003), and a maize N uptake, growth and yield model (Sinclair and Muchow 1995). An important feature of Adapt-N is its dynamic access to gridded high-resolution (4x4 km) weather data (precipitation, max-min temperature and solar radiation), which allows for field-specific and in-season adjustments to N application based on plant need. The weather data are derived from routines using the US National Oceanic & Atmospheric Administration's Rapid Update Cycle weather model (temperature) and operational Doppler radars (precipitation). The tool is highly flexible in terms of N management options with inputs for fall, spring or split applications of fertilizer-N and a range of manure types and compositions, as well as accounting for N inputs from rotation crops (soybean [Glycine max (L.) Merr.], sod, etc.). The Adapt-N tool generates precision N recommendations based on a mass balance approach according to:

$$N_{rec} = N_{\exp\_yld} - N_{crop\_now} - N_{soil\_now} - N_{rot\_credit} - N_{fut\_gain-loss} - N_{profit\_risk}$$

Where N_{rec} is the N rate recommendation (kg ha^{-1}); N_{exp_yld} is the crop N content needed to achieve the expected yield supplied by the user; N_{crop_now} and N_{soil_now} are the N content in the crop and soil as calculated by the PNM model for the current simulation date; N_{rot_credit} is the (partial) N credit from soybean crop rotation; $N_{fut\_gain-loss}$ is a probabilistic estimate of future N gains 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 factor that integrates corrections for fertilizer and grain prices, as well as a stochastic assessment of the relative profit risk of under-fertilization vs. over-fertilization.

The tool has been extensively validated using three separate independent datasets: The first is a comparison with the grower regular N management practices, conducted using 113 side-by-side strip trials in IA and NY (Sela et al. 2016a). Adapt-N was found to reduce the applied N by 34% without compromising crop yields, and led to an overall increase of \$65 ha^{-1} in profit compared to the grower regular practice. In a second validation set (Sela et al. 2016b), N recommendations by the Adapt-N tool were compared to those supplied by the Cornell N calculator (CNC, (Ketterings et al. 2003)), a static Stanford-type N recommendation tool. Using data from 16 multiple N rates trials conducted in NY, the measured Economically Optimum N Rate (EONR) was calculated and compared to both Adapt-N and the CNC. Adapt-N was found superior to the CNC, reducing the EONR RMSE from 62 kg ha^{-1} for the case of the CNC to 31 kg ha^{-1} for the case of Adapt-N. Lastly, the Adapt-N tool was compared to the Maximum Return to N (MRTN) recommendation method (Sawyer et al., 2006) using data from 25 multi-rate trials in IN, OH and WI (Sela et al., in preparation). Adapt-N was found to reconstruct the EONR better than the MRTN, reducing the EONR RMSE from 47 kg ha^{-1} for the case of the MRTN to 33 kg ha^{-1} for the case of Adapt-N. Altogether, these results built confidence in Adapt-N's ability to accurately simulate field conditions and the associated N dynamics.

This study employs the Adapt-N precision N management tool in multiple locations in the US Midwest using climatic data from multiple years, to specifically address the following research question: What is the potential of different N application timings and the use of N inhibitors to reduce environmental N losses?

2. Methodological approach

The analysis was performed on the five largest corn production states in the US: Indiana (IN), Illinois (IL), Iowa (IA), Minnesota (MN) and Nebraska (NE), accounting for 55% of all US corn production (USDA_NASS 2015). In each state five locations were selected, for a total of 25 locations (Fig. 1). For NE, the locations were restricted to the eastern, non-irrigated part of the state. In each location an extensive set of simulations were conducted to explore the production and environmental effects of N management approaches, fertilizer type, soil texture, organic matter percentage and climatic variability on crop growth and associated N losses in the context of the use of the Adapt-N tool. Eight different N management scenarios were simulated on an annual basis, spanning from Nov 30th to the Nov 29th of the following year. The N management scenarios were: a) Fall Anhydrous Ammonia (AA); b) Fall AA with Nitrapyrin, a nitrification inhibitor; c) Spring AA preplant; d) Spring AA preplant with Nitrapyrin; e) Spring Urea preplant; f) Spring Urea preplant with NBPT (Urease inhibitor) and DCD (nitrification inhibitor); g) Poly-coated (controlled release) Urea preplant; and h) Split application (starter + sidedress) of UAN. In each location, all N management scenarios were repeated using six years of climate data (2010-2015), 3 texture types (silty clay loam, loam and sandy loam), and two organic matter levels (high and low), for a total of 8100 simulations. In all simulations 12.5 Mg ha^{-1} (200 bu ha^{-1}) was used as the expected yield, a corn following soybean rotation was assumed, and planting date was fixed to May 1st.

The actual amount of N applied on fields during fall and spring preplant applications at the Midwest varies substantially according to the grower preferences and state recommendations. In this analysis 135 kg ha^{-1} (120 lbs ac^{-1}) of N was assumed for both fall and spring preplant applications. This is a conservative value, equivalent to 75% of the total N recommendation amount, based on the mean N recommendation for corn following soy for the states of IN, IL, IA and MN using the MRTN method (179 kg ha^{-1} or 160 lbs ac^{-1};Sawyer et al. 2006). The simulated application dates for the fall and spring preplant were November 30th and April 15th, respectively. For the case of the split N application scenario, a starter of 56 kg ha^{-1} (50 lbs ac^{-1}) was applied with planting (May 1st). To reduce the possibility of crop N deficiencies and underachievement of the expected yield, in all simulations the Adapt-N tool was used on June 25th (V8) to derive N recommendations needed to ensure yield for each case, and the respective additional N was applied if needed. This optimum precision management scenario therefore mostly avoids yield losses from insufficient N availability after excessive rainfall. Therefore, the total amount of N applied in each simulation varied depending on local conditions and both simulated and expected N losses.

Finally, the simulated data were used to compare for each N management scenario (i) the total N applied, (ii) the total grain N uptake, (iii) N use efficiency, (iv) total N losses and (v) the yield-scaled losses. Adapt-N reports the total N uptake for the whole plant, and doesn’t separate it by the plant components (e.g. grain). Therefore to estimate the grain N uptake, a ratio of 0.64 between grain N and total N uptake was used following Setiyono et al. (2010).

3. Results and discussion

3.1 Effect of N management on N inputs, crop N uptake and N use efficiency

All management scenarios resulted in relatively large variations in the total N applied, due to the effects of weather, soil texture and organic matter percentage (Fig 2a). On average, the highest amount of N was required for fall applications, and the lowest amount for split applications, while spring applications required intermediate values of total N amount. On average, fall application required 84 kg ha^{-1} (38%) more N than split applications (Table 2). In most simulations of fall applications, an additional in-season application of N was recommended by Adapt-N to prevent N deficiencies, averaging 104 kg ha^{-1}, 86% of the preplant amount. The effect of adding Nitrapyrin inhibitor on the total N required was found to vary between the fall and spring applications, with minimal effect for the case of fall application and larger effect for the case of Spring preplant application (mean difference of 0.38 kg N ha^{-1} and 18 kg N ha^{-1}, respectively). For the urea spring application, both the poly-coated (ESN) and the NBPT-DCD inhibitors had a similar effect, reducing total N required by 19 kg ha^{-1} and 21 kg ha^{-1}, respectively. The effect of all inhibitors on the total N applied was found to be statistically significant when subjected to paired t test (α=0.05, p<0.001). *Altogether, changing the timing of application from fall to spring or split application had a much larger effect on the amount of N required to prevent N deficiencies than the effect of any fertilizer inhibitor.*

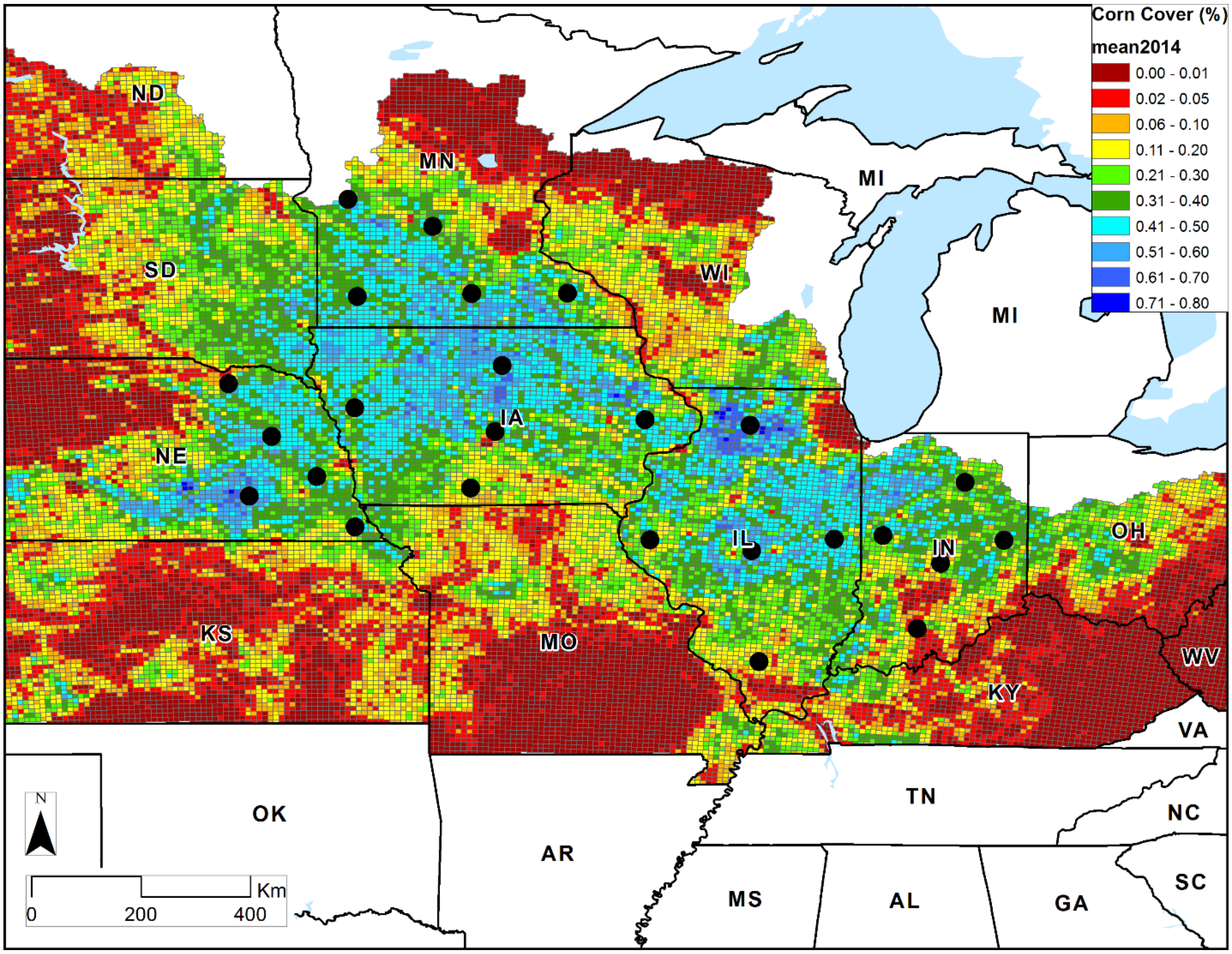

Figure 1. The 2014 corn cover fraction map for the US Midwest and the locations used for the simulations (marked black). Note that the Corn cover map is clipped to the extent of the Upper Mississippi River basin.

Figure 2b depicts the effect of N management on grain N uptake. Fall application had the lowest grain N uptake compared to all other simulated N managements. Both spring applications (with and without inhibitors) and the split application had a similar grain N uptake. Lower total N applied and a similar grain N uptake lead the split application to have the highest N use efficiency out of all simulated N management scenarios (Fig. 2c), calculated here as (grain N uptake / total N applied). Fall applications were found to have the lowest N use efficiency, a 43% decrease from the split application (Table 2).

Table 2. The difference in values of selected agronomic and environmental variables between seven N management approaches and split application (i.e. alternative N management approach - split application)

N management	Total N applied	Total Grain N uptake	NUE	Total N losses	Yield-scaled total N losses
	kg ha^{-1}		unitless	kg ha^{-1}	unitless
Fall AA	+84 (38%)	-7 (8%)	-0.33 (43%)	+82 (42%)	+1.25 (49%)
Fall-AA+Nitrapyrin	+84 (38%)	-7 (8%)	-0.33 (43%)	+81 (41%)	+1.23 (49%)
Spring-AA	+52 (27%)	+3 (3%)	-0.21 (27%)	+38 (25%)	+0.31 (19%)
Spring-AA+Nitrapyrin	+34 (20%)	+3 (3%)	-0.16 (21%)	+18 (14%)	+0.1 (7%)
Spring Urea	+42 (23%)	+5 (5%)	-0.17 (22%)	+25 (18%)	+0.14 (10%)
Spring poly coated Urea	+23 (14%)	+2 (2%)	-0.12 (16%)	+5 (4%)	0
Spring Urea NBPT DCD	+21 (13%)	+4 (4%)	-0.11 (14%)	+3 (3%)	-0.05 (4%)

Both AA and Urea inhibitors were found to offer about 10% increase in N use efficiency compared to the fertilizers without inhibitors.

3.2 Effect of N management on N losses

The effect of the different N management approaches on the simulated total N losses is presented in Figure 3a. To prevent the cases where lower simulated N losses mask lower simulated yield, the yield-scaled N losses (total N loss / total grain N uptake) are presented in Figure 3b. Shifting the timing of N application from fall to spring leads to a substantial decrease in N losses. Shifting the N management from fall or spring preplant to split applications further reduces N losses, with reductions ranging from 82 kg N ha^{-1} (42%) for the fall applications to 25 kg N ha^{-1} (18%) for the spring Urea application (Table 2). Interestingly, the spring AA application had on average higher losses than its respective Urea application (13 kg N ha^{-1}, 10%). This difference could be attributed to the different placement depth of the two fertilizers – Urea is placed in depth of 8 cm, and AA is placed at the depth of 23 cm to avoid losses to ammonia volatilization. This leads to higher average leaching losses for the AA fertilizer (63 kg N ha^{-1} compared with 52 kg N ha^{-1} for the Urea application). Fertilizer inhibitors were found to reduce N losses significantly, with an average reduction of ~20 kg N ha^{-1}. *Similar to the total required N, changing the timing of application from fall to spring or split application had a much larger effect on the amount of N losses than the effect of any fertilizer inhibitor.*

4. Conclusions

This analysis used Adapt-N, a commercially available precision N recommendation tool for maize, to evaluate the broader effects of different N management approaches on the total N required, NUE, and the associated environmental N losses. Split applications were found to have the highest NUE and the lowest environmental losses, and therefore they should be promoted for precision N management in corn production in the US Midwest. There is a potential to reduce environmental N losses by shifting N management from fall to spring and split applications, and by using fertilizer inhibitors. However, our results indicate that while fertilizer inhibitors are efficient in reducing N losses from spring preplant applications, they have only marginal, non-significant effect on reducing N losses when used on fall preplant application. Therefore, the largest potential in reducing N losses lies in shifting the timing of N applications from fall to the spring and to in-season applications in general, which is likely to be especially true in states with high annual precipitation. In all, these results show that precision N management has a broad context where the benefits of a precision tool like Adapt-N need to be combined with optimum timing, placement, or use of EEPs to achieve The greatest improvements in NUE and reductions in N losses. In other words, the concept of precision nitrogen management only makes sense if all aspects of the system are optimized.

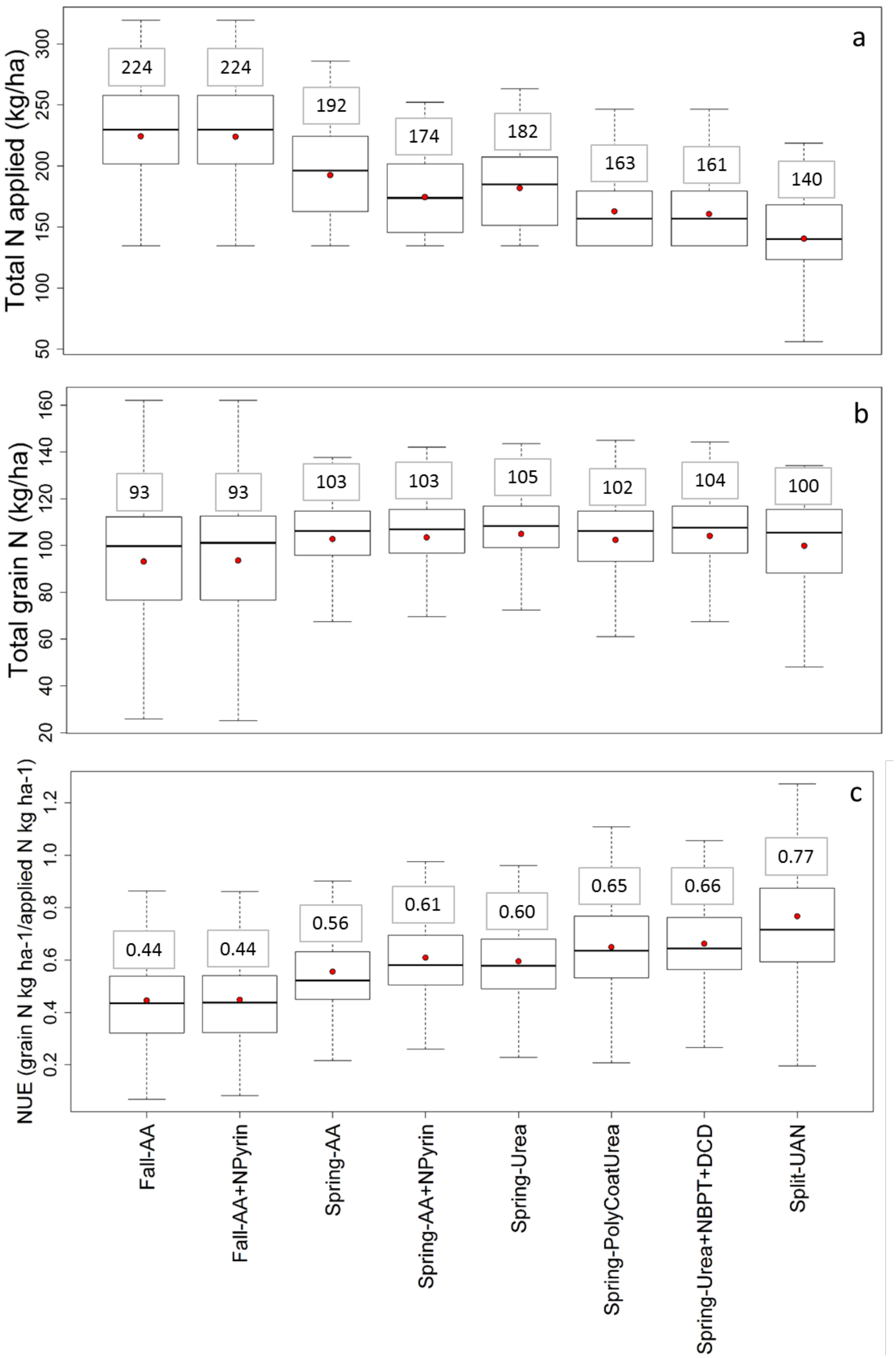

Figure 2. The effect of N management on Total N applied (a), total grain N uptake (b) and N use efficiency (c). The median value is indicated by a black line, the average value is indicated by a red dot and is also presented in the boxes. The x axis annotations in panel (c) apply to all panels.

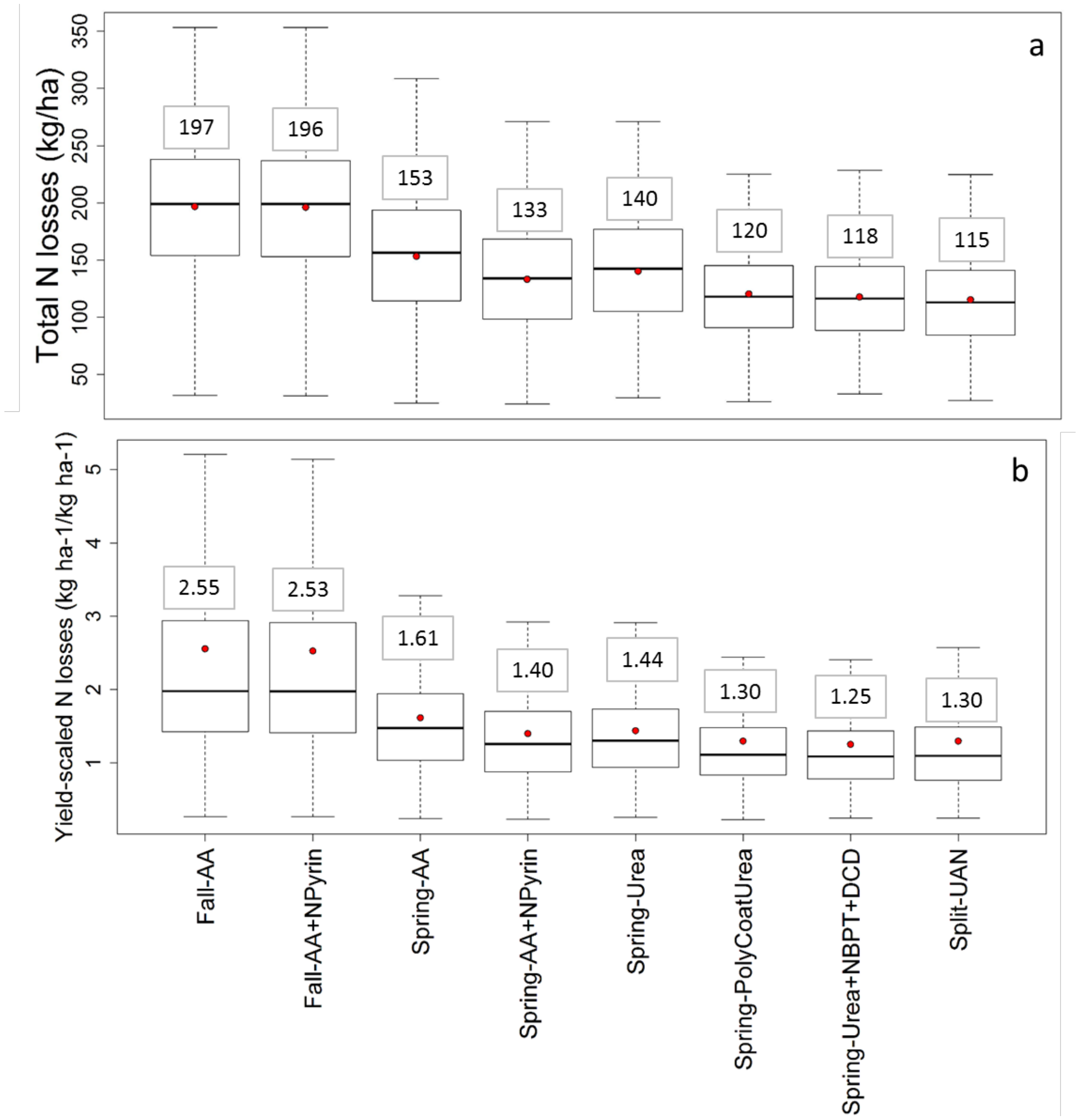

Figure 3. The effect of N management on Total N losses (a) and the yield-scaled total N losses. The median value is indicated by a black line, the average value is indicated by a red dot and is also presented in the boxes. The x axis annotations presented in panel (b) apply to both panels.

References

Böhlke, J.-K. (2002). Groundwater recharge and agricultural contamination. *Hydrogeology Journal*, *10*(1), 153–179. doi:10.1007/s10040-001-0183-3

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen. *Ecological Applications*, *8*(3), 559–568. doi:10.2307/2641247

Cassman, K. G., Dobermann, A., & Walters, D. T. (2002). Agroecosystems, Nitrogen-use Efficiency, and Nitrogen Management. *AMBIO: A Journal of the Human Environment*, *31*(2), 132–140. doi:10.1639/0044-7447(2002)031[0132:ANUEAN]2.0.CO;2

Diaz, R. J., & Rosenberg, R. (2008). Spreading dead zones and consequences for marine ecosystems. *Science (New York, N.Y.)*, *321*(5891), 926–929. doi:10.1126/science.1156401

Dinnes, D., Karlen, D., Jaynes, D., Kaspar, T., Hatfield, J., Colvin, T., & Cambardella, C. (2002). Nitrogen management strategies to reduce nitrate leaching in tile-drained midwestern soils. *Agronomy Journal*, *94*(1), 153–171.

Dodds, W. K., Bouska, W. W., Eitzmann, J. L., Pilger, T. J., Pitts, K. L., Riley, A. J., et al. (2009). Eutrophication of U.S. Freshwaters: Analysis of Potential Economic Damages. *Environmental Science & Technology*, *43*(1), 12–19. doi:10.1021/es801217q

Ferguson, R., Hergert, G., Schepers, J., Gotway, C., Cahoon, J., & Peterson, T. (2002). Site-specific nitrogen management of irrigated maize: Yield and soil residual nitrate effects. *Ssoil Science Society of America Journal*, *66*(2), 544–553.

Gruber, N., & Galloway, J. N. (2008). An Earth-system perspective of the global nitrogen cycle. *Nature*, *451*(7176), 293–296. doi:10.1038/nature06592

Gu, B., Ge, Y., Chang, S. X., Luo, W., & Chang, J. (2013). Nitrate in groundwater of China: Sources and driving forces. *Global Environmental Change*, *23*(5), 1112–1121. doi:10.1016/j.gloenvcha.2013.05.004

Halvorson, A. D., & Del Grosso, S. J. (2012). Nitrogen source and placement effects on soil nitrous oxide emissions from no-till corn. *Journal of environmental quality*, *41*(5), 1349–60. doi:10.2134/jeq2012.0129

Halvorson, A. D., Del Grosso, S. J., & Jantalia, C. P. (2011). Nitrogen source effects on soil nitrous oxide emissions from strip-till corn. *Journal of environmental quality*, *40*(6), 1775–86. doi:10.2134/jeq2011.0194

Halvorson, A. D., Snyder, C. S., Blaylock, A. D., & Del Grosso, S. J. (2014). Enhanced-Efficiency Nitrogen Fertilizers: Potential Role in Nitrous Oxide Emission Mitigation. *Agronomy Journal*, *106*(2), 715. doi:10.2134/agronj2013.0081

Hutson, J. L., & Wagenet, R. J. (2003). *Leaching Estimation And Chemistry Model: a process-based model of water and solute movement, transformations, plant uptake, and chemical reactions in the unsaturated zone* (No. R03-1). Ithaca.

Jaynes, D. B., & Colvin, T. S. (2006). Corn Yield and Nitrate Loss in Subsurface Drainage from Midseason Nitrogen Fertilizer Application. *Agronomy Journal*, *98*(6), 1479. doi:10.2134/agronj2006.0046

Ketterings, Q. M., Klausner, S. ., & Czymmek, K. J. (2003). *Nitrogen guidelines for field crops in New York* (Second rel.). Ithaca, New York: Cornell University. http://nmsp.cals.cornell.edu/publications/extension/Ndoc2003.pdf

Kitchen, N. R., Sudduth, K. A., Drummond, S. T., Scharf, P. C., Palm, H. L., Roberts, D. F., & Vories, E. D. (2010). Ground-Based Canopy Reflectance Sensing for Variable-Rate Nitrogen Corn

Fertilization. *Agronomy Journal*, *102*(1), 71–84. doi:10.2134/agronj2009.0114

McSwiney, C. P., & Robertson, G. P. (2005). Nonlinear response of N2O flux to incremental fertilizer addition in a continuous maize (Zea mays L.) cropping system. *Global Change Biology*, *11*(10), 1712–1719. doi:10.1111/j.1365-2486.2005.01040.x

Melkonian, J. J., van Es, H. M., & Joseph, L. (2005). *Precision Nitrogen Management model: simulation of nitrogen and water fluxes in the soil-crop-atmosphere continuum in maize (Zea mays L.) production systems.* (No. Version 1.0.). Cornell University, Ithaca, NY, U.S.A.: Dept. of Crop and Soil Sciences, Research series No. R05-2.

Mulvaney, R., Khan, S., Hoeft, R., & Brown, H. (2001). A soil organic nitrogen fraction that reduces the need for nitrogen fertilization. *Soil Science Society of America Journal*, *65*(4), 1164–1172.

National Atlas of the United States. (2011). *United States Average Annual Precipitation, 1990-2009*. Reston, VA: National Atlas of the United States. http://nationalatlas.gov/atlasftp.html

Parkin, T. B., & Hatfield, J. L. (2014). Enhanced Efficiency Fertilizers: Effect on Nitrous Oxide Emissions in Iowa. *Agronomy Journal*, *106*(2), 694. doi:10.2134/agronj2013.0219

Pennock, D. (2005). Precision conservation for co-management of carbon and nitrogen on the Canadian prairies. *Journall of soil and water conservation*, *60*(6), 396–401.

Robertson, G. P., & Vitousek, P. M. (2009). Nitrogen in Agriculture: Balancing the Cost of an Essential Resource. *Annual Review of Environment and Resources*, *34*(1), 97–125. doi:10.1146/annurev.environ.032108.105046

Sawyer, J., Nafziger, E., G., R., Bundy, L., Rehm, G., & Joern, B. (2006). *Concepts and rationale for regional nitrogen guidelines for corn*.

Scharf, P., Kitchen, N., Sudduth, K., Davis, J., Hubbard, V., & Lory, J. (2005). Field-scale variability in optimal nitrogen fertilizer rate for corn. *Agronomy Journal*, *97*(2), 452–461.

Schmidt, J. P., Hong, N., Dellinger, A., Beegle, D. B., & Lin, H. (2007). Hillslope Variability in Corn Response to Nitrogen Linked to In-Season Soil Moisture Redistribution. *Agronomy Journal*, *99*(1), 229–237. doi:10.2134/agronj2006.0187

Sela, S, van Es, H.M., Moebius-Clune, B.N., Marjerison, R., Melkonian, J., Moebius-Clune, D., Schindelbeck, R., and Gomes, S. (2016a), Adapt-N Outperforms Grower-Selected Nitrogen Rates in Northeast and Midwest USA Strip Trials. *Agronomy Journal*., Accepted. doi: 10.2134/agronj2015.0606

Sela, S., van Es, H.M., Moebius-Clune, B.N., Marjerison, R., Moebius-Clune, D., Schindelbeck, R., Severson, K., and Young, E. (2016b), Dynamic model improves agronomic and environmental outcomes for Corn N management over static approach. *Journal of Environmental Quality*. Under review

Setiyono, T. D., Walters, D. T., Cassman, K. G., Witt, C., & Dobermann, A. (2010). Estimating maize nutrient uptake requirements. *Field Crops Research*, *118*(2), 158–168. doi:10.1016/j.fcr.2010.05.006

Shahandeh, H., Wright, A. L., Hons, F. M., & Lascano, R. J. (2005). Spatial and Temporal Variation of Soil Nitrogen Parameters Related to Soil Texture and Corn Yield. *Agronomy Journal*, *97*(3), 772–782. doi:10.2134/agronj2004.0287

Sinclair, T., & Muchow, R. (1995). Effect of Nitrogen supply on Maize yield .1. Modeling physiological -responses. *AGRONOMY JOURNAL*, *87*(4), 632–641.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., et al. (2008). Greenhouse gas mitigation in agriculture. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, *363*(1492), 789–813. doi:10.1098/rstb.2007.2184

Stanger, T. F., & Lauer, J. G. (2008). Corn Grain Yield Response to Crop Rotation and Nitrogen over 35 Years. *Agronomy Journal*, *100*(3), 643–650. doi:10.2134/agronj2007.0280

Sutton, M. A., Oenema, O., Erisman, J. W., Leip, A., van Grinsven, H., & Winiwarter, W. (2011). Too much of a good thing. *Nature*, *472*(7342), 159–161. doi:10.1038/472159a

Tremblay, N., Bouroubi, Y. M., Bélec, C., Mullen, R. W., Kitchen, N. R., Thomason, W. E., et al. (2012). Corn Response to Nitrogen is Influenced by Soil Texture and Weather. *Agronomy Journal*, *104*(6), 1658–1671. doi:10.2134/agronj2012.0184

USDA ERS. 2015a. Fertilizer Use and Price. Retrieved from: http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx.

USDA_ERS. (2015b). Crop production practices for corn: Nutrient Use by Application Timing. http://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/tailored-reports-crop-production-practices.aspx#Pb68dfe82283345c6afd252ba6e332428_5_79iT0R0T0R0R0x5

USDA_NASS. (2015). Crop Production 2014 Summary. Retrieved from: http://www.usda.gov/nass/PUBS/TODAYRPT/cropan15.pdf.

van Es, H. ., Sogbedji, J. M., & Schindelbeck, R. (2006). Effect of manure application timing, crop, and soil type on nitrate leaching. *Journal of environmental quality*, *35*(2), 670–679. doi:10.2134/jeq2005.0143

van Es, H. M., Kay, B. D., Melkonian, J. J., & Sogbedji, J. M. (2007). Nitrogen Management Under Maize in Humid Regions: Case for a Dynamic Approach. In T. Bruulsema (Ed.), *Managing Crop Nutrition for Weather* (pp. 6–13). International Plant Nutrition Institute.

Venterea, R. T., & Coulter, J. A. (2015). Split Application of Urea Does Not Decrease and May Increase Nitrous Oxide Emissions in Rainfed Corn. *Agronomy Journal*, *107*(1), 337. doi:10.2134/agronj14.0411

Vitousek, P. M., Aber, J. D., Howarth, R. W., Likens, G. E., Matson, P. A., Schindler, D. W., et al. (1997). Technical Report: Human Alteration of the Global Nitrogen Cycle: Sources and Consequences. *Ecological Applications*, *7*(3), 737–750. doi:10.2307/2269431

Wortmann, C. S., Tarkalson, D. D., Shapiro, C. A., Dobermann, A. R., Ferguson, R. B., Hergert, G. W., & Walters, D. (2011). Nitrogen Use Efficiency of Irrigated Corn for Three Cropping Systems in Nebraska. *Agronomy Journal*, *103*(1), 76–84. doi:10.2134/agronj2010.0189

Zhu, Q., Schmidt, J. P., & Bryant, R. B. (2015). Maize (Zea mays L.) yield response to nitrogen as influenced by spatio-temporal variations of soil–water-topography dynamics. *Soil and Tillage Research*, *146*, 174–183. doi:10.1016/j.still.2014.10.006