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# A geostatistical approach to identify and mitigate agricultural nitrous oxide emission hotspots

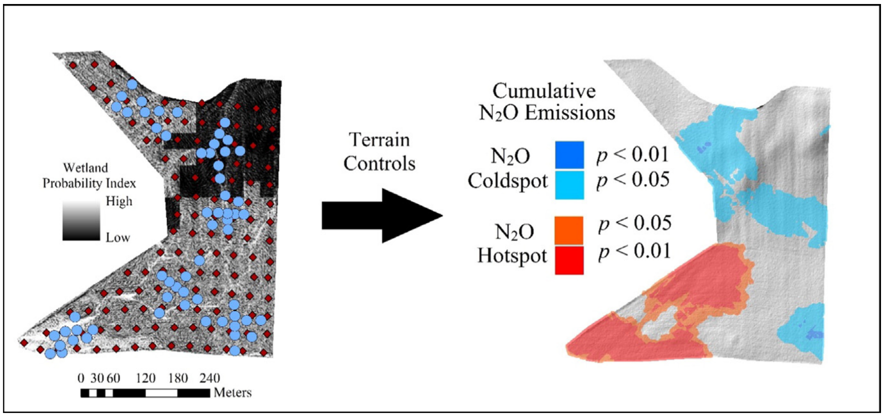
P.A. Turner [a,*], T.J. Griffis [a], D.J. Mulla [a], J.M. Baker [a,b], R.T. Venterea [a,b]

[a] *Department of Soil, Water, and Climate, University of Minnesota, 439 Borlaug Hall, 1991 Upper Buford Circle, St. Paul, MN 55108, USA*
[b] *United States Department of Agriculture – Agricultural Research Service, Soil and Water Management Unit, 1991 Upper Buford Circle, St. Paul, MN 55108, USA*

## HIGHLIGHTS

- Geospatial analyses resolved $N_2O$ emissions at fine spatial scales.
- Hotspots emitted $N_2O$ at rates >2-fold greater than non-hotspot locations.
- Targeted management of $N_2O$ hotspots could reduce emissions by 17%.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Anthropogenic emissions of nitrous oxide ($N_2O$), a trace gas with severe environmental costs, are greatest from agricultural soils amended with nitrogen (N) fertilizer. However, accurate $N_2O$ emission estimates at fine spatial scales are made difficult by their high variability, which represents a critical challenge for the management of $N_2O$ emissions. Here, static chamber measurements ($n = 60$) and soil samples ($n = 129$) were collected at approximately weekly intervals ($n = 6$) for 42-d immediately following the application of N in a southern Minnesota cornfield (15.6-ha), typical of the systems prevalent throughout the U.S. Corn Belt. These data were integrated into a geostatistical model that resolved $N_2O$ emissions at a high spatial resolution (1-m). Field-scale $N_2O$ emissions exhibited a high degree of spatial variability, and were partitioned into three classes of emission strength: hotspots, intermediate, and coldspots. Rates of emission from hotspots were 2-fold greater than non-hotspot locations. Consequently, 36% of the field-scale emissions could be attributed to hotspots, despite representing only 21% of the total field area. Variations in elevation caused hotspots to develop in predictable locations, which were prone to nutrient and moisture accumulation caused by terrain focusing. Because these features are relatively static, our data and analyses indicate that targeted management of hotspots could efficiently reduce field-scale emissions by as much 17%, a significant benefit considering the deleterious effects of atmospheric $N_2O$.

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*Abbreviations:* CV, coefficient of variation; DEM, digital elevation model; LiDAR, light detection and ranging; OC, ordinary cokriging; VNRA, variable rate nitrogen application; WPI, wetland probability index.

[*] Corresponding author.
*E-mail address:* turne289@umn.edu (P.A. Turner).

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## 1. Introduction

Nitrous oxide ($N_2O$) is a potent greenhouse gas (Hartmann et al., 2013) and the leading cause of stratospheric ozone loss (Ravishankara et al., 2009). In response to its deleterious environmental effects, efforts to mitigate agricultural emissions, which account for nearly 75% of the national anthropogenic source (US Department of State, 2014), are in development. Such efforts often focus on N management improvements (e.g., optimizing the source, depth, and timing of fertilizer) at the field or farm scale. Yet, the findings from these mitigation strategies have been highly variable (Venterea et al., 2016), in part because episodic and spatially variable emissions hinder accurate budget estimates (Mathieu et al., 2006; Velthof et al., 2000). For instance, field-scale $N_2O$ emission measurements with chambers can yield a coefficient of variation (CV) as high as 500% (Folorunso and Rolston, 1984; van den Pol-van Dasselaar et al., 1998), suggesting that our ability to accurately determine the outcome of mitigation practices is cause for concern. At fine sub-field spatial scales ($<1$ $m^2$ to 1000 $m^2$), $N_2O$ "hotspots" appear to be disproportionately strong sources (Parkin, 1987; van den Heuvel et al., 2009), yet their influence over cumulative field-scale emissions remains uncertain because high-resolution data are rarely available. For farmers to manage $N_2O$ emissions effectively, subfield-scale emission estimates are necessary to identify potential hotspots and to benchmark their effects on field-scale mitigation practices.

Light detection and ranging (LiDAR) digital elevation models (DEMs) are powerful tools that can help guide precision agriculture and conservation strategies (Galzki et al., 2011; Wan et al., 2014). When coupled with geospatial techniques, this emerging technology helps generate high-resolution maps of agriculturally relevant information such as the presence of hydric soils (Fink and Drohan, 2016), moisture content (Moore et al., 1993; Murphy et al., 2009), and soil nitrogen status (Weintraub et al., 2014) that allow farmers to focus extra attention and resources on critical areas. Furthermore, complex processes like methane emissions (Sundqvist et al., 2015) have been characterized using DEMs, suggesting that this technology can better resolve the field-scale spatial distribution of $N_2O$ emissions.

Indeed, differences in topography and landscape position have a strong influence on $N_2O$ emissions (Ambus, 1998; Ball et al., 1997) because terrain gradients redistribute moisture and nutrients that are necessary for the production of $N_2O$. Consequently, $N_2O$ emission frequency distributions are typically positively skewed by a few strong sources (Parkin, 1987; Velthof et al., 2000) observed at topographically low positions (Ambus, 1998). Here, terrain focusing enables the development of hotspots by concentrating organic matter, moisture, and nitrate ($NO_3^-$) into localized, but potentially predictable areas. Taken together, these soil characteristics can support disproportionately high rates of denitrification (Groffman et al., 2009) that we posit are capable of sustaining high $N_2O$ emissions. However, field-scale emission distribution maps remain coarse, since an unrealistic number of static chambers are required to resolve the high variability, implying poor constraints on hotspots.

With the aid of DEMs and geospatial analyses, denitrification hotspots can be isolated and mapped by pinpointing locations with the highest probability of moisture and $NO_3^-$ accumulation (Anderson et al., 2015). We propose that a similar approach can resolve the distribution of $N_2O$ emissions at a high spatial resolution that will guide targeted mitigation practices. Here, we examine the spatial distribution of $N_2O$ fluxes and cumulative emissions in a strip-tilled cornfield to address three questions: 1) can DEMs help predict where $N_2O$ hotspots will develop on the landscape; 2) how significant are hotspots in the cumulative field-scale budget; and 3) how can DEMs be used to guide N management and $N_2O$ mitigation?

## 2. Materials and methods

### 2.1. Site description and experimental design

The tile-drained, corn-soybean rotation research field (15.6-ha) was located on a private farm 11-km south of Northfield, Minnesota (44°21′37.2″N, 93°12′14.8″W). The predominant underlying soil is a Prinsburg silty clay loam (Typic Endoaquolls, USDA Classification) overlying a loam. Measurements were made during the corn (*Zea mays*, L.) phase in 2014 on DOY 126, 134, 150, 156, 161, and 168. The field was strip-tilled prior to planting and fertilized with 32% urea ammonium sulfate (UAS) on DOY 125 at a rate of 140 kg N $ha^{-1}$.

A 3-m micrometeorological tower was installed on the west side of the field to measure air temperature (VP-4; Decagon Devices, Pullman, WA, USA). Observations were recorded with a data logger at 5-min intervals and averaged hourly (Model EM50; Decagon Devices, Pullman, WA, USA).

All soil and chamber sample locations were georeferenced using a GPS device (GeoXH; Trimble, Sunnyvale, CA, USA) connected to a Mi-Fi mobile hotspot (model 2200; Verizon Wireless, Wallingford, CT, USA) that boosted the horizontal accuracy to 0.1 m. Spatial data were analyzed using ArcMap (ArcGIS v.10.2; ESRI Inc., Redlands, CA, USA).

To capture the effects of terrain on $N_2O$ emissions and to ensure potential hotspots were included in the measurement campaign, a Wetland Probability Index (WPI) map was created (ArcGIS v.10.2; ESRI Inc., Redlands, CA, USA) to guide the experimental design. The WPI is a regression function of four factors: the presence of hydric soils, slope, profile curvature, and a compound topographic index (CTI) that is a function of flow accumulation and slope. The WPI provides a relative metric to describe the likelihood that water will pond at a specific location and has been used to identify areas for efficient wetland reclamation (Wan et al., 2014). The WPI was chosen rather than the widely used soil wetness index (SWI), because the WPI incorporates drainage (hydric soils), a recognized shortcoming of the idealized SWI (Murphy et al., 2009). In the context of $N_2O$ production, field locations with wetland terrain characteristics are likely to accumulate moisture and nutrients and are thus candidates for hotspot formation. These areas are likely to experience more frequent and prolonged periods of soil saturation than upland areas, in part because of low slopes and elevation. Using high-resolution (1-m) DEM data (Minnesota Geospatial Information Office) and soil survey information, each position on the landscape was assigned a relative WPI value of 0 to 1 (Wan et al., 2014).

Since the natural movement of soil moisture is not confined to the explicit 1-m WPI grid, the highest spatial resolution is not necessarily appropriate for direct comparison with a dependent variable (Sørensen and Seibert, 2007). For instance, contour cropping, crop residues, buffer strips and microtopography can affect the movement of moisture. To minimize these uncertainties, we have reduced the WPI resolution to 10-m (Anderson et al., 2015; Zhang and Montgomery, 1994) for direct comparison of $N_2O$ emission measurements and surface characteristics. All other analyses used the high-resolution WPI data set.

Because terrain differences can influence emissions, a stratified sampling design based on WPI was used to characterize emission heterogeneity. Groups ($n = 6$) of chambers ($n = 10$) were installed in the field across a range of WPI values on each of the sample dates. Measurements were taken at approximately weekly intervals for 42-d immediately after fertilization (DOY 125). Previous experiments in this field indicate that $N_2O$ fluxes are highest in the 20 to 50-d following fertilization (Baker et al., 2014; Fassbinder et al., 2013). Beyond this time frame, $N_2O$ fluxes decline (Baker et al., 2014; Turner et al., 2016a) and as a result, the cumulative emission budget is most sensitive to loss during this brief period.