Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL089949

Key Points:
- Daily TROPOMI data provide new opportunities to observe regional cropland NOx emissions from space
- Soil NOx pulsing is identified throughout the growing season with a NOx maximum observed when soils dry to ~30% volumetric soil moisture
- Cropland NOx emissions peak at the onset of the growing season as determined by TROPOMI NO2 enhancements and a box model framework

Supporting Information:
- Supporting Information S1

Correspondence to:
D. E. Huber, dehuber@umich.edu

Citation:
Huber, D. E., Steiner, A. L., & Kort, E. A. (2020). Daily cropland soil NOx emissions identified by TROPOMI and SMAP. Geophysical Research Letters, 47, e2020GL089949. https://doi.org/10.1029/2020GL089949

Received 19 JUL 2020
Accepted 25 OCT 2020
Accepted article online 29 OCT 2020

Plain Language Summary Soils are a known source of atmospheric nitrogen oxides (NOx = NO + NO2), a pollutant that contributes to poor air quality. In cropland regions, where nitrogen-rich fertilizers are applied to soils, NOx emissions can be significantly enhanced. We use satellite observations of nitrogen dioxide (NO2) from TROPOMI (TROPOspheric Monitoring Instrument) to quantify the soil-driven contribution to the amount of NOx in the atmosphere in a cropland region in Mississippi, USA. At the daily level, we use TROPOMI measurements together with soil moisture observations from the SMAP (Soil Moisture Active Passive) satellite to show that soil moisture plays an important role in regulating the amount of NOx that cropland soils release. At the seasonal level, we see the largest NOx contribution from soils toward the beginning of the growing season (May–June).

1. Introduction
Soils are a significant source of nitrogen oxides (NOx = NO + NO2) to the atmosphere, contributing up to 40% of the nitrogen dioxide (NO2) column over cropland during Northern Hemisphere summer months (Hudman et al., 2012; Vinken et al., 2014). Fossil NOx emissions, the largest source of NOx in the troposphere, decreased on average by 5.9% year−1 from 2005–2017, increasing the relative contribution from soil NOx to overall NOx emissions (Jiang et al., 2018; Silvern et al., 2019). NOx is a primary air pollutant associated with the formation of secondary pollutants including ozone (O3) and nitrogen-based aerosols (Jenkins & Clemitshaw, 2000). NOx and its subsequent oxidation products are not only detrimental to human health, but they can also cause adverse impacts for plants and other living organisms (Ashmore, 2005; Kampa & Castanas, 2008). As soil NOx continues to represent a larger portion of total global NOx, it will be increasingly important to understand its emission on finer temporal and spatial scales.

Soil NOx is primarily emitted in the form of nitric oxide (NO) with emissions driven by microbial processes within the soil surface layer (Pilegaard, 2013). The activity of NO-producing bacteria is determined by environmental conditions such as water-filled pore space (WFPS), soil temperature, and defining soil characteristics such as texture, bulk density, and nitrogen availability (Ludwig et al., 2001). WFPS plays a key role in controlling the magnitude of soil NOx emissions, as the activity of bacteria that drive emissions is highly dependent on the ratio of water to oxygen in the soil pore space. The relative magnitude of soil NOx emissions as a function of WFPS is typically represented by a Poisson function, with weakest emissions at extreme lower and upper limits of WFPS and strongest relative emissions between 20% and 65% WFPS (Hudman et al., 2012; Pilegaard, 2013), dependent upon specific soil characteristics. Increased nitrogen availability in cropland soils, largely due to fertilizer application, greatly enhances soil NOx emissions...
(Bouwman et al., 2002; Oikawa et al., 2015), making croplands important sources contributing to the regional NOx budget.

Current process understanding of soil NOx emissions has been driven by small-scale (~1 m) chamber studies, with emissions identified from a variety of soil and ecosystem types (e.g., Eberwein et al., 2020; Levine et al., 1996; Roelle et al., 2001; Schindlbacher et al., 2004). These and other observational studies of soil NOx fluxes have been used to develop process-based emissions models to estimate soil NOx emissions, such as the Berkeley Dalhousie Soil NOX Parameterization (BDSNP) (Hudman et al., 2012). BDSNP has been implemented into chemical transport models, including the GEOS-Chem global model and CMAQ regional model (Hudman et al., 2012; Rasool et al., 2016). BDSNP represents the effects of environmental variables on the magnitude of emissions, including WFPS, soil temperature, soil nitrogen availability, soil biome, and the contribution to emissions from soil NOx pulsing. NOx pulsing refers to enhanced emissions that can occur after the first soil wetting following an extended dry period. The wetting of dry soil can reinvigorate previously dormant soil bacteria, resulting in NO emissions pulses that can be many times the prepulse emissions magnitude (Kim et al., 2012). The pulsing mechanism within the BDSNP is based on Yan et al. (2005), which activates once soils dry to a volumetric soil moisture (VSM) of 17.5% or less for at least three consecutive days prior to soil wetting.

Space-based observations are particularly useful for understanding soil NOx emissions in regions where ground-based observations are not available. Using SCIAMACHY (Scanning Imaging Absorption spectroMeter for Atmospheric CHartographY) and a soil NOx emissions model, Bertram et al. (2005) identified daily soil NOx pulse emissions of up to 25 ng N m^{-2} s^{-1} in an agricultural region in Montana, with peak emissions at the beginning of the growing season. A global study used observed NO2 vertical column densities (VCDs) from the Ozone Monitoring Instrument (OMI) and the GEOS-Chem model to quantify average June Northern Hemisphere soil NOx emissions at 2.5° resolution (Vinken et al., 2014). Multiple satellite studies have observed soil NOx emissions and pulsing in the African Sahel (Hickman et al., 2018; Jaeglé et al., 2004; Zörner et al., 2016), where NO2 column enhancements up to 100% of the prepulse VCDs are attributed to soil NOx pulsing associated with the onset of the rainy season following months of dry weather (Zörner et al., 2016).

While satellite observations have been used to identify soil NOx emissions in the past, no satellite study has yet constrained emissions at near-daily regional scales and in conjunction with satellite-observed process controls. In this study, we utilize satellite observations of tropospheric NO2 from TROPOMI (TROPOspheric Monitoring Instrument) to quantify the contribution of cropland soils to regional NOx emissions in the lower Mississippi (MS) River Valley on daily to seasonal scales in 2018 and 2019. The unprecedented resolution of the TROPOMI product allows for soil emission processes to be evaluated using observed NO2 enhancements at spatiotemporal scales unresolvable with previous space-based NO2 products. We identify a robust seasonally varying contribution from cropland soils to NOx emissions, with the largest contributions during the late spring months (May–June), with emissions patterns matching predictions by the BDSNP model. Further, we use daily TROPOMI tropospheric NO2 observations in conjunction with Soil Moisture Active Passive (SMAP) VSM observations to identify NOx pulse events in the days following precipitation, a consistently observed feature for this domain distinct from the historical definition of soil NOx pulsing.

2. Data

Level 2 tropospheric NO2 VCD measurements are obtained from the TROPOMI instrument onboard the Sentinel-5P satellite (Veefkind et al., 2012). TROPOMI was launched in 2017 and measures NO2 VCDs with a nadir spatial resolution of 3.5 × 7 km² for observations between 30 April 2018 and 6 August 2019 and a resolution of 3.5 × 5.5 km² from 6 August 2019 onward. TROPOMI uses observed radiation in the near-ultraviolet and visible together with a chemical transport model to estimate tropospheric NO2 VCDs. We filter the TROPOMI data using only pixels with “flag_value” greater than or equal to 0.75 (van Geffen et al., 2019) to remove pixels that have unreliable measurements (e.g., due to the presence of clouds). To ensure that a sufficient number of pixels remain within the region of interest after applying this filter, we require that (1) a threshold of 30 pixels must remain within the domain after filtering based on the flag value alone and
the number of filtered pixels divided by the total number of pixels before filtering must be greater than or equal to 25%. If at least one of these conditions is not met, then the daily swath is excluded from analysis.

Level 3 surface VSM observations are obtained from the SMAP satellite (Entekhabi et al., 2010). SMAP was launched in 2015 and uses a passive microwave radiometer to observe surface radiation in the L-band (1.4 GHz) to determine VSM mixing ratios in approximately the top 5 cm of soil. Measuring radiation at these wavelengths allows observations to be made in even very cloudy conditions, resulting in more temporally homogenous observations than TROPOMI NO2 observations, which are impacted by the presence of clouds. To ensure that SMAP VSM is measured from soils and not overlying vegetation, we apply a filter to remove pixels with vegetation water content greater than 5 kg m\(^{-2}\) (Colliander et al., 2017).

Daily winds are derived from ERA5 reanalysis (Hersbach et al., 2020) for 18:00 – 19:00 UTC, coincident with the TROPOMI overpass. Daily precipitation totals are from the NOAA CPC Gauge-Based precipitation analysis (Chen et al., 2008). For the quantification of soil NOx emissions, anthropogenic NOx emissions are obtained from the 2014 gridded National Emissions Inventory (NEI) (Strum et al., 2017).

3. NO2 and Cropland in the Mississippi River Valley

We define a 0.75 × 0.75° cropland domain located in the southern United States within the MS Delta (Figure 1a, solid white box). Soybean is the dominant crop type, representing nearly 80% of the cropland area as determined by the CropScape database (Han et al., 2012). This region experiences year-round precipitation, with 28% and 19% of the annual precipitation occurring during the spring and summer seasons, respectively. This region regularly experiences changes in soil moisture due to rainfall as well as seasonal flooding from the MS River, which makes this an ideal location for studying the impact of soil moisture changes on soil NOx emissions. Multiple power plants are located north of the study region that can substantially contribute to the local NOx signature. Limiting our analysis to the MS Delta, which is located more than 125 km from the nearest major urban region or major power plants, greatly minimizes the influence of fossil NOx emissions on the cropland NOx signature. The cropland region has an east-west extent of approximately 70 km and is adjacent to forest on both the eastern and western edges of the region.

Individual TROPOMI overpasses can spatially resolve increased NO2 VCDs over the cropland domain during drydown periods in days following precipitation (Figure 1). NO2 VCDs are relatively low over the cropland region 5 days before a rainfall event (Figure 1b; 14 May 2019) yet increase 5 days after (Figure 1c; 24 May 2019). Common features in the NO2 signal are evident on both days, including the anthropogenic
NOx signature from fuel combustion sources near Little Rock, AR, and Memphis, TN. However, the higher NO2 VCDs present over the cropland after the rainfall event (Figure 1c) suggest crop-driven soil NOx emissions in this region.

4. Results

4.1. NO2 Column Enhancement

We use forested regions upwind of the cropland domain as reference sites to estimate daily average background TROPOMI NO2 VCDs (Figure 1a, dashed white boxes). These reference sites provide nearby, “clean” upwind domains containing few major NOx sources, which are ideal for background quantification. The reference sites facilitate the calculation of the NO2 column enhancement over the cropland domain by subtracting the average inflow background NO2 VCD from the average cropland NO2 VCD. This calculated difference reveals the contribution from cropland soils to the NO2 column for each day of available TROPOMI observations. A positive enhancement indicates higher cropland NO2 VCDs for that day, and a negative enhancement indicates higher upwind NO2 VCDs for that day. Upwind domains have been used in previous satellite studies to estimate background concentrations of atmospheric trace gases to derive enhancements (e.g., Kort et al., 2012) and offer a slight improvement over defining enhancements when using the lowest decile of observations (e.g., de Gouw et al., 2020). The high density of TROPOMI observations enables statistically robust daily evaluation of enhancements even considering the 30-pixel requirement (see section 2) for both the upwind and cropland domains.

Depending upon the predominant wind direction, one of two different 0.75 × 0.75° upwind domains are defined for calculating the daily NO2 enhancement: one east and one west relative to the cropland domain (Figure 1a and supporting information Figure S1). Days with a predominantly northly wind (340–20°) are excluded due to the potential influence of urban emissions from the Memphis metropolitan region. Over the analysis period (2018–2019), the east domain is used for 37% of the daily enhancements, the west domain is utilized for 50% of the daily enhancements, and about 13% of days are excluded due to the presence of a predominately northerly wind.

4.2. Seasonal NO2 Enhancements and Soil NOx Emissions Estimate

Monthly averaged NO2 enhancements are largest in May 2018 and June 2019 (Figure 2a), months that coincide with the onset of the growing season and an increase in agricultural activity. The average monthly enhancements during these months are between 0.4 and 0.5 × 1015 molecules cm−2. Enhancements in winter months are mostly negligible, coinciding with a relative lack of agricultural activity and resulting in similar NO2 VCDs over the cropland and upwind domains. Additionally, the timing of crop planting in the region largely shifts from May in 2018 to June in 2019 (USDA, 2019; Figure S2), suggesting that the shift in the largest TROPOMI enhancements from May in 2018 to June in 2019 is a direct result of the delayed planting of crops within the cropland domain. The magnitudes of these peak monthly enhancements are consistent with Vinken et al. (2014) that estimated an absolute contribution from soils to the NO2 column over cropland in the midwestern United States of approximately 0.6 × 1015 molecules cm−2 using the OMI satellite. However, Vinken et al. (2014) did not identify a contribution from soils to the NO2 column over the MS Delta cropland domain used within this study. This may be due to the coarser resolution of the model used (2.5°), coarser resolution of OMI relative to TROPOMI, or the higher fossil NOx emissions during the study period (2005) that potentially masked the soil NOx signal.

To estimate soil NOx emissions \( E_{\text{soil}} \) (ng N m\(^{-2}\) s\(^{-1}\)) from the cropland domain using TROPOMI NO2 observations, we apply a box model that accounts for sources and sinks of NOx:

\[
E_{\text{soil}} = \frac{U \Delta (NO_2 \text{ VCD})}{L} + \frac{V_d \text{ NO}_2 \text{ VCD}}{Z_{\text{PBL}}} + \frac{\text{NO}_2 \text{ VCD}}{\tau} - E_{\text{NEI}}
\]

where the first term on the right-hand side \( \frac{U \Delta (NO_2 \text{ VCD})}{L} \) represents the advection of NOx into the box, \( U \) is the average wind speed (m s\(^{-1}\)) over the cropland domain, \( \Delta (NO_2 \text{ VCD}) \) is the spatial TROPOMI NO2 column enhancement (molecule m\(^{-2}\)) between the cropland and upwind domain, and \( L \) is the distance
(m) from edge to edge between the cropland and the upwind domain (Figure 1a). The second term on the right-hand side represents the deposition of NOx, where \( V_d \) is the NO\(_2\) deposition velocity (m s\(^{-1}\)) from Yang et al. (2010), \( \text{NO}_2_{\text{VCD}} \) is the NO\(_2\) VCD (molecule m\(^{-2}\)) over the cropland domain, and \( Z_{\text{PBL}} \) is the boundary layer height estimated at a constant 10\(^3\)-m height throughout the year. The third term on the right-hand side represents the NOx chemical loss rate, where \( \frac{1}{\tau} \) is the inverse NOx lifetime (s\(^{-1}\)). The NOx lifetime \( \tau \) is estimated to vary sinusoidally throughout a year, with a peak lifetime on 21 December and a minimum lifetime on 21 June. \( E_{\text{NEI}} \) is the anthropogenic NOx emissions (molecule m\(^{-2}\) s\(^{-1}\)) from the 2014 NEI inventory. Chemical production as a source of NOx is assumed to be negligible.

Using Equation 1, we calculate daily box model estimates of soil NOx emissions and average to monthly values (Figure 2b). We present three different emissions scenarios with a varying minimum June NOx lifetime of 3, 5, and 7 hr. Martin et al. (2003) estimated NOx lifetime of approximately 5 hr in the summer at this latitude, and we increase and decrease the summer lifetime by ±2 hr to illustrate the sensitivity of the box model emissions estimates to NOx lifetime assumptions. All three scenarios converge to a maximum December NOx lifetime of 15 hr. The largest emissions occur during the late spring and early summer, with minimal emissions during the winter. Our monthly average box model emissions estimates range from 15 to 34 ng N m\(^{-2}\) s\(^{-1}\) in May and June, with the range driven by the influence of NOx lifetime as described in recent studies (e.g., Laughner & Cohen, 2019; Shah et al., 2020).

Figure 2. (a) Mean monthly TROPOMI tropospheric NO\(_2\) VCD (gray bars; left axis) and mean monthly NO\(_2\) column enhancement (blue line; right axis). NO\(_2\) enhancements represent the mean monthly contribution from cropland soils to the NO\(_2\) column. Error bars show standard error of the mean. (b) Monthly average soil NOx emissions estimated using the soil NOx emissions box model and the BDSNP model. All three box model scenarios converge to a December NOx lifetime of 15 hr.
For the same domain and time frame, we estimate emissions using the BDSNP model. As inputs for the BDSNP, we use WFPS calculated from SMAP surface VSM observations, ERA5 soil temperature (Hersbach et al., 2020), and soil nitrogen availability data available from the MEGAN biogenic emissions model framework (Guenther et al., 2006). WFPS is calculated from the ratio of SMAP VSM to estimated soil porosity within the cropland domain (Linn & Doran, 1984). BDSNP soil NOx emission magnitudes are roughly half that of the box model emissions with a 5-hr June lifetime; however, the month-to-month variability between the two methods is consistent (Figure 2b). Both methods estimate relative peak emissions in May of 2018 and June of 2019. Further, both methods experience similar month-to-month variability during the growing season. The exception to this is September of 2019, during which BDSNP estimates the largest monthly average emissions for the entire study period.

Our satellite-based soil NOx emission estimates are largely consistent with small-scale chamber studies as well as satellite studies. A chamber study over cropland in North Carolina, United States, measured average NO emissions on the order of 20.2 ± 19 ng N m⁻² s⁻¹ during spring and summer (Roelle et al., 2001), while a chamber study in high-temperature croplands in Southern California observed median emissions of 20 ng N m⁻² s⁻¹ with individual measurements up to 900 ng N m⁻² s⁻¹ (Oikawa et al., 2015). Satellite studies show similar ranges, with Bertram et al. (2005) using SCIAMACHY to estimate May soil NOx emissions from cropland in Montana, United States, with daily values ranging from 10 to 25 ng N m⁻² s⁻¹ and Jaeglé et al. (2004) used the Global Ozone Monitoring Experiment (GOME) instrument to estimate average June soil NOx emissions from the Sahel region of 20 ng N m⁻² s⁻¹ under the assumption of a 7-hr NOx lifetime.

### 4.3. Daily-Scale NO2 Enhancements and Multiday NOx Pulse Events

To observe the relationship between soil emissions and soil moisture within the cropland domain, we use SMAP VSM observations to identify soil drydown events that occur in the days following precipitation and observe changes in daily TROPOMI NO2 enhancements during those events. We identify days in 2018 and 2019 between May and October with heavy (≥1 cm) precipitation followed by at least 1 week without heavy precipitation. We require observed VSM to increase to greater than 0.4 cm³ cm⁻² without heavy precipitation. We observe VSM to increase to greater than 0.4 cm³ cm⁻² in response to the initial precipitation and then decrease in the week following without a subsequent increase. If a relative peak in TROPOMI NO2 enhancements occurs as SMAP observations decrease in the week following precipitation, then the peak enhancement is associated with a “drydown NOx pulse” event.

Using the above criteria, we identify nine potential drydown NOx pulse events between May and October in 2018 and 2019. Two drydown events are excluded due to the absence of TROPOMI data. One event is excluded due to persistently high TROPOMI enhancements occurring before, during, and after soil drying. We align the remaining six events onto the same day axis, defining Day 0 as the day of relative peak NO2 enhancement following the decrease in soil moisture (Figure 3). NO2 enhancements increase as the soil dries and enhancements reach a relative maximum on Day 0, coincident with VSM decreasing below a value of 0.3 cm³ cm⁻³. This suggests a local SMAP VSM threshold of approximately 30%, an emergent observation below which soils must decrease for drydown pulse emissions to reach a maximum. A previous study has shown that SMAP observations may exhibit faster soil drying than in situ measurements (Shellito et al., 2016), which would suggest that the observed threshold may be offset from in situ measured soil moisture. Notably, in a chamber study on cropland NO emissions in California, Oikawa et al. (2015) found that peak soil NOx emissions occurred at roughly 30% VSM, suggesting that this 30% threshold may hold broader significance for cropland soils. We evaluate the significance of each Day 0 NO2 column enhancement by conducting two-sample t tests between upwind and cropland domain observations for all six events, confirming the significance of the observed enhancements (p values < 0.05 for five of six events, p value = 0.09 for remaining event).

The drydown NOx pulsing we observe is distinct from NOx pulsing as classically described in the literature. Soil NOx pulsing is historically characterized by a substantial increase in soil NO emissions within hours after soil wetting following an antecedent dry period (Davidson, 1992; Kim et al., 2012). Here, we observe peak enhancements between 4 and 8 days after precipitation and in the absence of preceding dry periods (Figure 3). A multiday lag between soil wetting and peak soil NOx pulse emissions is not unprecedented.
and is hypothesized in Hall et al. (1996). A lag of 2–7 days has been observed (Hickman et al., 2018; McCalley & Sparks, 2008); however, both studies experience preceding dry conditions, a distinct difference from our findings.

We include BDSNP soil NOx emissions estimates for the same period as the drydown pulse events to compare with the behavior in the observed NO2 column enhancements (Figure 3d). While BDSNP emissions increase following precipitation, emissions continue to increase even after the observed TROPOMI enhancements peak on day 0. This is a result of the modeled soil moisture dependency within the BDSNP which is designed to peak at 13% VSM (30% WFPS) in the cropland domain, causing BDSNP estimates to continue increasing as soils continue drying after Day 0. This may explain the largest BDSNP emissions during September 2019 (Figure 2), as that month was the only time during the study period during which VSM...
values approached, but did not reach, 13% for multiple days, causing the BDSNP to estimate greater emissions during that month. This implies that for some cropland soils, BDSNP may overestimate emissions at lower VSM, may underestimate emissions at higher VSM, and may not capture the pulsing during drydown periods identified in the satellite record.

5. Conclusions

We find that daily spatial TROPOMI NO2 enhancements can be successfully used to quantify the contribution from cropland soil to the NO2 column at the daily and the seasonal scales and can sufficiently resolve the spatial variability associated with soil NOx emissions. The resolution of the TROPOMI NO2 product provides a much higher density of observations compared to previous satellite products, allowing for soil NOx emissions to be resolved in spatially confined regions like the MS Delta. We show that daily TROPOMI NO2 observations can be applied to a box model framework to quantify seasonal cropland soil NOx emissions for 2018 and 2019. Monthly NO2 enhancements peak in late spring and early summer, times at which agricultural activity increases and enhances cropland soil NOx emissions. Peak monthly NO2 enhancements shift from May in 2018 to June in 2019, a shift that coincides with a shift in the timing of crop planting between 2018 and 2019. This suggests that seasonal land management practices directly influence the contribution from cropland soils to the NO2 column. Soil NOx box model emissions estimates achieve an annual maximum ranging from 15 to 34 ng N m⁻² s⁻¹, values that are within the range of other estimated soil NOx emissions. Box model emissions estimates are higher than BDSNP estimates, with the box model exhibiting similar variability in annual soil NOx emissions as predicted by the BDSNP model. The lower BDSNP estimates may arise as a consequence of not capturing emissions that peak at VSM values above 13% in the cropland domain. Additionally, TROPOMI NO2 enhancements can resolve drydown NOx pulse emissions over cropland in conjunction with decreasing SMAP surface VSM observations in the days following precipitation. This highlights a unique application of two space-based instruments to observe daily environmental process controls that contribute to enhanced cropland NOx emissions. The daily soil contribution to the NO2 column during peak drydown NOx pulsing ranges from $0.2 \times 10^{15}$ molecules cm⁻² (October 2018) to $0.8 \times 10^{15}$ molecules cm⁻² (June 2018), consistent with more abundant available soil nitrogen at the beginning of the growing season (May/June) and less abundant at the end of the growing season (October). During drydown NOx pulsing, TROPOMI NO2 enhancements peak in the week following precipitation once SMAP measurements decrease below a threshold of 30% VSM (65% WFPS). This implies that not all nonarid soils experience peak emissions at 30% WFPS as is currently implemented in the BDSNP and that BDSNP emissions may be underestimated or overestimated in regions where different soil moisture responses exist.

Data Availability Statement

Data used in this paper are downloaded from the Sentinel-5P Pre-Operations Data Hub (TROPOMI, https://s5phub.copernicus.eu/dhus/), the National Snow and Ice Data Center (SMAP, https://nsidc.org/data/SPL3SMP_E/versions/3), and the ECMWF Climate Data Store (ERA winds, https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview).

References

Ashmore, M. R. (2005). Assessing the future global impacts of ozone on vegetation. Plant, Cell and Environment, 28(8), 949–964. https://doi.org/10.1111/j.1365-3040.2005.01341.x
Bertram, T. H., Heckel, A., Richter, A., Burrows, J. P., & Cohen, R. C. (2005). Satellite measurements of daily variations in soil NOx emissions. Geophysical Research Letters, 32, L24812. https://doi.org/10.1029/2005GL024640
Bouwman, A. F., Boumans, L. J. M., & Batjes, N. H. (2002). Emissions of N2O and NO from fertilized fields: Summary of available measurement data. Global Biogeochemical Cycles, 16(4), 1058. https://doi.org/10.1029/2001GB001811
Chen, M., Shi, W., Xie, P., Silva, V. B. S., Kousky, V. E., Higgins, R. W., & Janowiak, J. E. (2008). Assessing objective techniques for gauge-based analyses of global daily precipitation. Journal of Geophysical Research, 113, D04110. https://doi.org/10.1029/2007JD009132
Colliander, A., Jackson, T. J., Bindlish, R., Chan, S., Das, N., Kim, S. B., et al. (2017). Validation of SMAP surface soil moisture products with core validation sites. Remote Sensing of Environment, 191, 215–231. https://doi.org/10.1016/j.rse.2017.01.021
Davidson, E. A. (1992). Pulses of nitric oxide and nitrous oxide flux following wetting of dry soil: An assessment of probable sources and importance relative to annual fluxes. Ecological Bulletins, 42, 149–155.
Strum, M., Eyth, A., & Vukovich, J. (2017). Preparation of emissions inventories for the version 7, 2014 emissions modeling platform for NATA. U.S. Environmental Protection Agency. Available online at. https://gaftp.epa.gov/Air_Quality_Data/emismod/2014/v1/reports/2014v7.0_2014_EmisMod_TSDv1.pdf

U.S. Department of Agriculture (USDA) (2019). National agricultural statistics service. Crop progress. Accessed November 3, https://usda.library.cornell.edu/concern/publications/8336h188j?locale=en

van Geffen, J. H. G., Eskes, H. J., Boersma, K. F., Maasakkers, J. D., & Veefkind, J. P. (2019). TROPOMI ATBD of the total and tropospheric NO2 data products. KNMI, 2019. Retrieved from http://www.tropomi.eu/sites/default/files/publicSentinel-5P-TROPOMI-ATBD-NO2-data-products.pdf

Veefkind, J. P., Aben, I., McMullan, K., Förster, H., de Vries, J., Otter, G., et al. (2012). TROPOMI on the ESA Sentinel-5 precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. Remote Sensing of Environment, 120, 70–83. https://doi.org/10.1016/j.rse.2011.09.027

Vinken, G. C. M., Boersma, K. F., Maasakkers, J. D., Adon, M., & Martin, R. v. (2014). Worldwide biogenic soil NOx emissions inferred from OMI NO2 observations. Atmospheric Chemistry and Physics, 14, 10,363–10,381. https://doi.org/10.5194/acp-14-10363-2014

Yan, X., Ohara, T., & Akimoto, H. (2005). Statistical modeling of global soil NOX emissions. Global Biogeochemical Cycles, 19, GB3019. https://doi.org/10.1029/2004GB002376

Yang, R., Hayashi, K., Zhu, B., Li, F., & Yan, X. (2010). Atmospheric NH3 and NO2 concentration and nitrogen deposition in an agricultural catchment of eastern China. Science of the Total Environment, 408(20), 4624–4632. https://doi.org/10.1016/j.scitotenv.2010.06.006

Zörner, J., Penning De Vries, M., Beirle, S., Sihler, H., Veres, P. R., Williams, J., & Wagner, T. (2016). Multi-satellite sensor study on precipitation-induced emission pulses of NOx from soils in semi-arid ecosystems. Atmospheric Chemistry and Physics, 16(14), 9457–9487. https://doi.org/10.5194/acp-16-9457-2016