

Deriving Cropland N₂O Emissions from Space-Based NO₂ Observations

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Abstract: Croplands are the largest anthropogenic source of nitrous oxide (N₂O), a potent greenhouse gas and ozone-depleting substance. Agricultural emissions produce small atmospheric signals with high spatiotemporal variability presenting a large observational challenge. If capable, space-based observations could characterize
10 cropland N₂O emissions from farmlands across the world. No current satellite can resolve near-surface N₂O variations from cropland emissions. However, satellite observations of nitrogen dioxide (NO₂), a component of NO_x along with nitric oxide (NO), capture cropland emissions. NO, which quickly converts to NO₂ in the atmosphere, and N₂O are co-emitted from soils. Both gases are produced by microbial soil processes and are emitted in large
15 amounts as a result of excess nitrogen from applied fertilizer. Given their co-emission in croplands, we ask: Can satellite NO₂ observations be used to infer N₂O emissions? We examine coincident airborne N₂O and NO_x measurements downwind of California croplands to characterize N₂O:NO_x emission relationships from farms. We use these emission ratios to transform estimates of agricultural NO_x emissions derived from space-based TROPOMI NO₂ observations to N₂O emissions. We compare these estimates to independent ground and airborne studies in the
20 US Corn Belt and Mississippi River Valley. Space-based estimates are broadly consistent with these ground and airborne studies, suggesting that satellite NO₂ observations can be used to infer cropland N₂O emissions. Further refinement of a NO₂ proxy approach for cropland N₂O emissions has the potential to expand observational capabilities to constrain regional and global cropland N₂O emissions and inform process models.

1 Introduction:

Nitrous oxide (N₂O) is a potent greenhouse gas and ozone-depleting substance with sizable anthropogenic
25 emissions. In a 100-year time frame, N₂O has a global warming potential 298 times that of carbon dioxide (Butterbach-Bahl et al., 2013; Ravishankara et al., 2009). With a long atmospheric lifetime (over 100 years) and no tropospheric sink, N₂O emitted from the surface travels to the stratosphere where it can react with excited oxygen atoms to produce reactive nitrogen oxide radicals that deplete stratospheric ozone. N₂O is now the largest
30 contributor to stratospheric ozone depletion of actively emitted anthropogenic gases (Ravishankara et al., 2009). Since the 1700's the atmospheric concentration of N₂O has increased by over 60 parts per billion (ppb) (Tian et al., 2024), with an accelerating rate in recent years (Liang et al., 2022).

Agriculture is a dominant source of N₂O emissions, contributing 3.8 (2.5-5.8) Tg N₂O-N per year, or about 22%
35 (15%-34%) of global emissions, from 2007 to 2016, with a 30% increase over the past four decades due to nitrogen fertilization (Tian et al., 2020). This trend is expected to accelerate due to the growing demand for food and resources that support agricultural industries as well as waste and industrial processes, highlighting the urgent need for mitigation efforts (Davidson and Kanter, 2014).

Much of what we know about agricultural N₂O emissions is the result of near-surface N₂O measurements from soil
40 flux chambers. Observations from chamber systems range from ~10 samples per day (automatic chambers) (Rowlings et al., 2015; Sihi et al., 2020) to as infrequently as daily or monthly scales (manual chambers) (Griffis et al., 2013). The small spatial extent of chamber measurements, along with the availability of coincident auxiliary data (e.g., soil moisture, N application rates), permits robust mechanistic analyses of soil N₂O emissions. However, given the spatial heterogeneity of N₂O emissions (Lawrence et al., 2021), the small spatial resolution (~1m²) of chamber measurements becomes a limitation when assessing emissions at larger spatial scales. Eddy covariance methods can

45 be used to study N₂O emissions at the field scale, with sensitivity to surface emissions from upwind soils of ~10 to 1000 m² (di Marco et al., 2005). Observational constraints at much larger scales are possible with tall (~100's of meters in height) tower measurements of N₂O, which are interpreted with atmospheric transport and inverse modeling to infer N₂O emissions. This provides emissions information integrated over several hundred kilometers at a monthly temporal resolution (Chen et al., 2016; Griffis et al., 2013; Nevison et al., 2018, 2023).

50 More recently, airborne sampling approaches have demonstrated the potential to bridge the scale gap from flux chambers/eddy-flux to tall-towers. Depending on their flight altitude, airborne measurements can resolve N₂O emissions at the farm (~1-2 km) scale (Gvakharia et al., 2020) while sampling an area of several hundred kilometers (Dacic et al., 2024; Desjardins et al., 2015; Eckl et al., 2021; Gvakharia et al., 2020; Herrera et al., 2021; Jimenez et al., 2005; Kort et al., 2008; Xiang et al., 2013). The limitation of airborne observations is that they capture short time windows and sample targeted regions as part of campaigns such as CalNex (2010) (Xiang et al., 2013), FEAST (2017) (Gvakharia et al., 2020) and MAIZE (2021 & 2022) (Dacic et al., 2024; Kort et al., 2022, 2024a, 2024b).

55 Current observational methods to constrain N₂O emissions for the study of process-level emission controls or mitigation strategies are currently limited to the targeted ground and airborne approaches detailed above. A remote-sensing, space-based solution would have the potential to assess agricultural N₂O emissions at key spatiotemporal scales and broaden the spatial extent of studies beyond those limited by targeted ground and airborne measurements. 60 However, presently, we cannot directly measure surface-level N₂O signals from cropland emissions with a space-based platform. A promising opportunity, however, lies in the widespread remote sensing of nitrogen dioxide (NO₂). Nitric oxide (NO) is co-emitted with N₂O from agricultural soils (Davidson et al., 2000), and the NO is largely oxidized to NO₂ within seconds to minutes after emission (Jacob, 1999). Given that N₂O and NO are co-emitted and their emission patterns are driven by similar variables (e.g., fertilizer application) (Harrison et al., 1995; Sanhueza et al., 1990), variability in atmospheric NO₂ concentrations from agricultural soils may serve as a useful proxy for 65 corresponding N₂O emissions. Space-based NO₂ observations track spatiotemporal variations in NO₂ in both urban (Acker et al., 2025; Adams et al., 2023; Goldberg et al., 2019a, b, 2021, 2024; Ialongo et al., 2020; Park et al., 2022) and agricultural (Ghude et al., 2010; Huber et al., 2020, 2024; Lin et al., 2023) areas, and have done so for decades (Gonzalez Abad et al., 2019). Beyond the existence of NO₂ instrumentation in space, the relatively short lifetime of 70 NO₂ means emissions of NO₂ lead to large enhancements concentrated in the boundary layer, providing a large signal to observe. For N₂O, in contrast, emissions add only a very small enhancement over large background values (often less than 1ppb signals on background over 330ppb, Dacic et al., 2024), which presents an observational challenge.

75 In this work, we explore the potential of using space-based NO₂ observations as a proxy for agricultural N₂O emissions. We first discuss the driving mechanisms for N₂O and NO (NO_x) from managed croplands. We then use coincident airborne observations of NO and NO₂ (NO_x) and N₂O from the California Research at the Nexus of Air Quality and Climate Change (CalNex) campaign conducted in California in 2010 to derive N₂O-to-NO_x emission ratios for large spatial regions commensurate with satellite remote sensing of NO₂. The aircraft sampling captures 80 integrated emissions ratios that include heterogeneity of emissions in response to a number of driving process-level variables. We hypothesize that we can apply the observed emission ratio distribution to NO_x emissions derived from satellite NO₂ observations to obtain an estimate of N₂O emissions from space-based observations. This then enables observational analyses that cover large regions of the world and can track changes over time. We evaluate this possibility for the corn belt and the Mississippi River Valley in the USA.

2 Emissions of N₂O and NO from Managed Croplands

85 N₂O and NO emissions in agricultural soils result from the microbial processes of nitrification and denitrification, with N₂O predominating during denitrification (Baggs, 2008; Chen et al., 1995; Müller et al., 2003) and NO during nitrification (Skiba et al., 1993). Soil moisture influences these processes, where high water-filled pore space (WFPS) favors denitrification and low WFPS favors nitrification. This moisture dependency contributes to large emissions of N₂O and NO following rainfall events (Kim et al., 2012; Scholes et al., 1997), and poorly drained soils

90 are known to emit more N₂O than well-drained soils, which is an important management consideration for N₂O reduction strategies (Lawrence et al., 2021). Drier soils favor lower N₂O:NO emission ratios, often close to or less than unity, whereas wet soils can have higher emission ratios (Anderson and Levine, 1987; Davidson, 1992; Johansson and Sanhueza, 1988; Lipschultz et al., 1981; Tortoso and Hutchinson, 1990). Crop type also influences the N₂O:NO ratio (Anderson and Levine, 1987).

95 Fertilizer application is the most important common driver of NO and N₂O emissions, and fertilized soils have higher emissions of both trace gases (Harrison et al., 1995; Liu et al., 2017; Sanhueza et al., 1990; Shepherd et al., 1991). In the atmosphere, NO rapidly converts to NO₂, which together is referred to as NO_x (NO + NO₂). The accumulation of fertilizer is hypothesized to drive large post-rainfall emissions of N₂O (Cardenas et al., 1993; Johansson, 1984; Johansson and Sanhueza, 1988; Levine et al., 1996) and NO_x (Ghude et al., 2010; Jaeglé et al., 2004; Oikawa et al., 2015; Scholes et al., 1997; Smith et al., 1997).

100 Given the link between fertilizer application and emissions of NO and N₂O, we hypothesize that spatiotemporal patterns in NO_x emissions from croplands may be a useful proxy to estimate agricultural N₂O emissions. Over extended spatial and temporal scales that incorporate a variety of soil conditions and crop types, the variability in N₂O:NO emissions should be reduced compared to shorter, more localized observations, such as those made in chamber studies. This integrating effect may increase the fidelity of using emissions ratios to derive N₂O emissions.

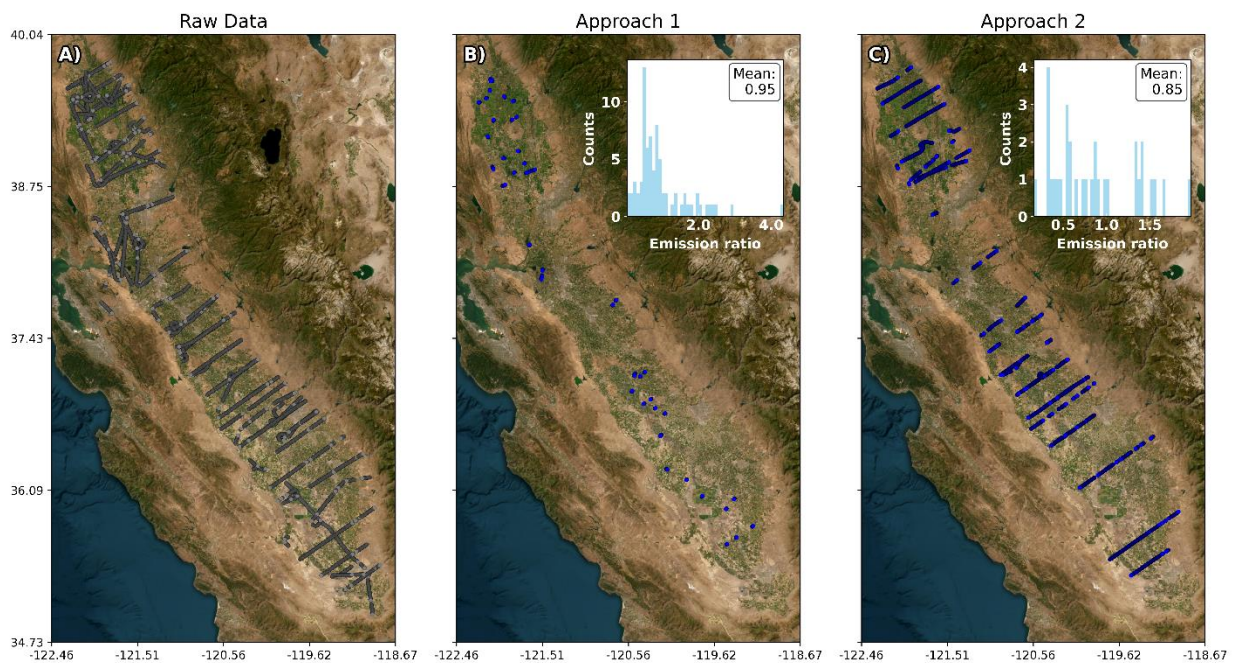
3 Deriving Emission Ratios from CalNex Airborne N₂O, NO, and NO₂ Observations

110 Satellite observations of NO₂ from TROPOMI or TEMPO, with ground pixel sizes in the range of 5.5x3.5 - 2x4.75 km, used to derive cropland NO_x emissions will be sensitive to the integrated emissions from entire farms and multi-farm conglomerates and counties (~250 km² (Merlos and Hijmans, 2020)). To characterize the cropland emission behavior at comparable spatial scales, we use airborne sampling of N₂O and NO_x to determine an emissions relationship between these gases downwind of agricultural fields. Very few airborne campaigns have been made with continuous, high-accuracy, high-precision measurements of N₂O and NO_x (NO + NO₂) in agricultural regions. For the analysis here we use observations from one of the few campaigns that collected such measurements, the CalNex campaign in 2010 (Fig. 1A), which sampled the San Joaquin and Sacramento Valleys during 6 flights between May 7 and June 18, 2010 (Data available at: <https://csl.noaa.gov/projects/calnex/>). In-flight instrumentation included the Harvard/National Center for Atmospheric Research's (NCAR) Dual Quantum Cascade Laser Spectrometer for measurement of N₂O (Jimenez et al., 2005; Kort et al., 2011), and a chemiluminescence sensor for NO and NO₂ (Pollack et al., 2010; Ryerson et al., 1999, 2001, 2003). During CalNex, measurements of these gases were reported at a 1s rate, and we applied an additional 5-second centered rolling average. In this study, we isolate cropland regions by restricting our analysis to locations >0.04° (~3.7 – 4.4 km) from regions with emissions in the top 1% of the National Emissions Inventory (NEI) (Strum et al., 2017), and to periods when the aircraft was below 500m elevation.

125 Literature from chamber studies often report the emission relationships between NO and N₂O. Chamber measurements of soil emissions typically directly observe NO prior to substantial conversion to NO₂. In this work we determine N₂O:NO_x molecular ratios from the aircraft, in order to provide a factor that can be multiplied directly to a soil NO_x emissions estimate to generate N₂O emissions. The soil NO_x estimate could be generated from a range of different approaches, including from space-based NO₂ observations as we demonstrate here. While soil emissions of NO_x are predominantly NO, when observed from aircraft or satellite downwind of emissions, the majority of this NO has been converted to NO₂ (Goldberg et al., 2024 A; Goldberg et al., 2024 B; Kimbrough et al., 2017; Pilegaard et al., 2013; Seinfeld and Pandis, 2012; Williams et al., 1992).

130 For the CalNex observations, we consider both the NO₂ and NO measurements to capture the total quantity of NO_x emitted from the agricultural fields. We note the majority of the NO emitted has converted to NO₂ by the time the air has reached the aircraft, so if the subsequent analysis was performed only with NO₂, the results are very similar.

135 We apply two methods to characterize $N_2O:NO_x$ emission relationships from the CalNex airborne dataset. Figure 1B and 1C show histograms of derived emission ratios corresponding to each approach overlaid over flight maps with the location of data from those approaches. We use these emission ratios to characterize the heterogeneity in the empirical relationship between N_2O and NO_x at the farm to multi-farm scale. Below, we briefly outline each approach.



140 **Figure 1: Flight maps corresponding to data remaining after filtering steps in A) the raw CalNex dataset filtered for data within the agricultural fields and away from high NO_2 -emission areas, B) in *approach 1* and C) in *approach 2*. A histogram showing the distribution of binned molecular emission ratios determined in each respective approach is overlaid upon the map. Satellite imagery credit: Esri.**

145 *Approach 1* seeks to isolate concentration enhancement signals from cropland emissions within ~ 10 km of the aircraft to determine aircraft-derived $N_2O:NO_x$ emission relationships. We isolate concentration enhancements from near-field cropland emissions by filtering for distinct peaks in N_2O concentration and accounting for the chemical loss of NO_2 . A similar method has been performed to isolate plumes from nearby natural gas flares in the Bakken (Gvakharia et al., 2017). First, we determine N_2O , NO and NO_2 enhancements as the concentration above the 5th percentile of a rolling, centered, one-minute window for every data point from the CalNex airborne NO , NO_2 and N_2O dataset. This background approach means enhancements only emerge when they correspond to a plume of this width or narrower. Using a gaussian plume model, a source of this width would be $\sim 2-4$ km in distance upwind of the aircraft assuming moderate instability. Sources further than this will impact the background but not the enhancement. In this way, distant (20-100km) pollution sources do not impact our analysis. We then isolate cases that are separated by at least 5 seconds in time ($\sim 500+$ meters in space) where N_2O concentration is enhanced and NO , NO_2 , and N_2O 's concentration perturbations exceed instrument noise. We require 8 or more observations where the range from minimum to maximum N_2O concentration enhancement exceeds 0.09 ppb. Cases are removed if their slopes are below zero, as these do not imply co-emission.

160 We account for photochemical loss of NO_2 by estimating the distance from the source to the observed N_2O enhancement. Assuming the width of an observed enhancement represents a plume's width, we estimate the transport distance from the plume's origin using rural dispersion parameters from Zannetti et al., (2013). We assume

a moderately unstable atmosphere during CalNex. Based on daily wind conditions, we estimate the transport time relative to the average NO₂ lifetime and add this NO₂ lost due to photochemistry back to the observed NO₂ enhancement, creating a chemically corrected NO₂ enhancement. We then add the observed NO enhancement, thus
165 generating a NO_x enhancement corresponding to emissions from the agricultural field. For each isolated plume, we use the observed N₂O enhancement and chemically corrected NO_x enhancement to calculate a N₂O:NO_x emission ratio using type-II ranged major axis regression. For each plume, the slope represents a unique emission ratio.

The average chemistry corrected enhancement emission ratio (referred to as the emission ratio from here forward) is 0.95 ppb N₂O / ppb NO_x, a slightly lower value than the ratio (1.36 ppb N₂O / ppb NO_x) if chemical loss is not
170 accounted for. This adjustment is small compared to the variance we see in the ratio. The final dataset using this approach results in 76 individual plumes observed in the nearfield of croplands to derive the N₂O:NO_x emission ratio, as shown in Fig. 1B. The resultant molecular emissions ratio distribution will encompass variation due to a number of variable drivers of emissions in the upwind region (crop type, fertilizer, soil moisture, etc...).

Approach 2 incorporates the airborne measurements at a broader spatial scale. With this method, we isolate
175 individual flight legs, or portions of the aircraft transects, that are perpendicular to daily wind direction and downwind of agricultural fields. We then characterize each flight leg's N₂O:NO_x relationship and treat it as a unique concentration enhancement ratio. Similar to *approach 1*, we derive the background by defining the enhancement as the concentration greater than the 5th percentile of a rolling centered one-minute window around every data point.

Approach 2, rather than isolating small-scale cropland emissions as in *approach 1*, derives an integrated
180 concentration enhancement relationship of N₂O to NO_x across a portion of the cropland. We assume impacts from chemical loss are averaged out across flight legs and therefore do not directly correct for the chemical loss of NO₂. Therefore, for *approach 2*, we assume enhancement ratios are equivalent to emission ratios. *Approach 2* yields an average molecular emissions ratio of 0.85, determined using type-II ranged major axis regression on the N₂O and NO_x concentration enhancements. Flight legs considered in this method are shown in Fig. 1C. This approach
185 includes more observational data than *approach 1*, integrating larger domains into the determined emissions ratio.

As seen in Fig. 1, we obtain similar mean N₂O:NO_x ratios from each method, demonstrating that the relationship is robust to methodological differences and assumptions. The distributions of the derived N₂O:NO_x values for each
190 approach are also comparable. The Kruskal-Wallis test performed between these two distributions yields a p-value of 0.7827, suggesting no significant difference in median or distribution, and the Welch's t-test, compared between them, shows there is no significant difference between the emission ratios. Emission ratios range between 0.038 and 4.34 ppb N₂O / ppb NO_x for *approach 1* and 0.16 and 1.97 ppb N₂O / ppb NO_x for *approach 2*, reflecting expected heterogeneity in N₂O:NO_x ratio over agricultural lands, and demonstrating that increasing the spatial scale aggregated to create these ratios dampens variability. The N₂O:NO_x values we observe are in line with N₂O:NO
195 values in literature from soil-chamber measurements, which report highly heterogeneous emission ratios typically ranging from ~0.1-10, but that in rare cases can be as high as 100. (Johansson and Sanhueza, 1988; Tortoso and Hutchinson, 1990). This variation occurs as a function of factors such as fertilizer application, crop-type, and other management and environmental factors (Anderson and Levine, 1987; Davidson, 1992; Johansson and Sanhueza, 1988; Lipschultz et al., 1981). As expected with the larger spatial scale of our airborne approach, integrating over
200 variable soil conditions and crop types, our ratios show less variability than prior soil chamber studies and decrease in variability as more observations are aggregated (from *approach 1* to *approach 2*). More coincident observations of N₂O and NO_x downwind of a variety of agricultural domains under varied conditions could lead to refinement and improvement on the approach outlined here. In the following sections, we use emission ratios derived from *approach 2*, though there is little sensitivity to this choice.

4 Deriving N₂O from Satellite NO₂ Observations:

205 With N₂O:NO_x emissions ratios derived from the aircraft measurements, N₂O emissions can be determined from space if soil NO_x emissions are calculated from space-based NO₂ observations. Many different methods can be applied to derive NO_x emissions estimates from satellite NO₂ observations. For instance, Huber et al., (2020) applied

a box model to estimate NO_x emissions from TROPOMI-observed NO₂ enhancements within the Mississippi River Valley, Ghude et al., (2010) inferred top-down soil NO_x emissions from OMI by mass balance, and Lin et al., (2023) estimated soil NO_x emissions from TROPOMI based on seasonal variation.

Here, we use a simple chemical box model and TROPOMI NO₂ observations to demonstrate quantification of agricultural N₂O using space-based NO₂ observations. We focus our analysis on three regions (Figure 2) in the USA where independent ground and airborne measurement campaigns have previously been conducted to determine N₂O emissions, providing a bases for direct comparison with this new approach. These independent studies of N₂O emissions, conducted in different locations and with different methods, provides an opportunity for evaluation of our emissions ratio method. This evaluation is a strong challenge for this method, as the emissions ratios are determined from aircraft data collected over California in 2010, and crop-type, management practice, soil moisture, and other driving variables can be quite different in these central US regions.

In this work, we use TROPOMI Version 02.04.00 (S5P_L2_NO2_HiR_2) NO₂ retrievals (KNMI). TROPOMI observations are filtered for a quality assurance value greater than or equal to 0.75, indicating high-quality data per the operational retrieval (Van Geffen et al., 2020). We use these TROPOMI NO₂ observations in a chemical box model to determine agricultural NO_x emissions in the Mississippi River Valley, Nebraska, and Iowa, employing a similar data-model approach as previously outlined in Huber et al., (2020). The chemical box model defined by equation 1:

$$E_{soil,NO_2} = \frac{U\Delta(NO_{2,VCD})}{X} + \frac{V\Delta(NO_{2,VCD})}{Y} + \frac{V_d(NO_{2,VCD})}{Z_{PBL}} + \frac{NO_{2,VCD}}{t} - E_{NEI}, \quad (1)$$

The first two terms in Eq. 1 captures advection, representing NO₂ advected into and out of a box model domain. Here, U represents the average zonal wind speed (m/s) across the box of interest and X is the distance of the east-to-west edge of the box model domain. V denotes meridional winds and Y denotes north-to-south edge distance along the box model domain. In this work, $\Delta(NO_{2,VCD})$ denotes the mean TROPOMI NO₂ column enhancement above a background, here defined as the 5th percentile of NO₂ within the box. This enhancement is used as a proxy for the spatial gradient across the domain, where the background value is representative of the inflow into the box and the resulting enhancement is representative of the outflow. This is similar to approaches used in previous studies (Godlowska et al., 2023; Huber et al., 2020; Li et al., 2021). The third term denotes deposition, where V_d denotes the deposition velocity (m/s) from Yang et al., (2010) (Deposition velocity by month: DJF, 0.02 cm/s; MAM, 0.16 cm/s; JJA, 0.29 cm/s; SON, 0.06 cm/s). NO_{2,VCD} is the average NO₂ vertical column density in the box model domain and Z_{PBL} is the boundary layer height estimate over the box model domain. Similar to Huber et al., (2020), Z_{PBL} is set to 1000m over the course of the study. The fourth term represents chemical loss, where NO_{2,VCD} again denotes the NO₂ vertical column density in the box model domain and “t” represents the lifetime of NO_x. The final term E_{NEI} denotes the average fossil fuel NO_x emissions in the box model domain from the 2014 NEI inventory (Strum et al., 2017), averaged monthly to eliminate noise. This model outputs an estimate of non-fossil fuel NO_x emissions for the box model domain.

Lifetime values used for the analyses were derived from Martin et al., (2003). In Huber et al., (2020) lifetimes of 3, 5, and 7 hours were used (also derived from Martin et al., (2003)) to constrain the influence of lifetime on the analysis. We opt to use a lifetime value of 3 hours for this main text, but variation in results due to these lifetime values of 5 (moderate) and 7 (slow) hours can be observed in supplemental figures 1 & 2. As was observed in Huber et al., (2020) lifetime has a large impact on NO_x emission estimates.

In this work, we analyze TROPOMI NO₂ retrievals on a daily scale. The size and location of the analysis domain vary depending upon the region of interest, but have a minimum size 0.75° x 0.75° to be consistent with the domain size used in Huber et al. (2020) . We additionally exclude TROPOMI overpasses from the study if they incorporate less than 30 TROPOMI NO₂ observations in our box model domain for the Lawrence et al., (2021) and Gvakharia et al., (2020) comparison, or less than 120 TROPOMI NO₂ observations for the larger Dacic et al., (2024) comparison region. Once NO_x emissions are derived using Equation 1, we multiply soil NO_x emissions (E_{soil,NO_x} , units of

nmole/m²/sec), by the aircraft-derived N₂O:NO_x molecular emission ratio to obtain an estimate of N₂O flux, E_{soil,N_2O} , units of nmole/m²/sec (Equation 2).

$$E_{soil,N_2O} = (ER_{N_2O:NO_x})E_{soil,NO_x}, \quad (2)$$

To incorporate the variability in the observationally derived emission ratio on estimated N₂O emissions in this analysis, we employ a Monte Carlo resampling approach where we propagate variation in the N₂O:NO_x emission ratio through to N₂O emissions. We iterate through the daily average values of TROPOMI-derived NO_x emissions and multiply each by the distribution of emission ratios shown in Fig. 1C to derive all possible N₂O emissions from the variation in N₂O:NO_x. We then randomly sample one of these N₂O realizations over 10,000 iterations to create a distribution of TROPOMI NO₂-derived N₂O emissions. The 2.5th percentile and the 97.5th percentile define the 95% confidence interval, with the mean providing a central estimate. This confidence interval reflects uncertainty in the analysis reflecting the emission ratio derived in Section 3 and not absolute uncertainty in soil NO_x emissions. Since our focus in this work is evaluating the viability of the emissions ratio proxy approach, we focus on uncertainty of the N₂O:NO_x emission ratios and quantify its impact on resulting N₂O emission estimates. Depending on what approach one takes to generate NO_x emissions estimates from space-based NO₂ observations, other uncertainty would be added. For the box model we use here as an illustrative example, we conduct a sensitivity analysis to lifetime and deposition velocity (model terms 3 & 4), shown in supplementary Fig. 1-4.

5 Comparison with Independent Estimates of N₂O

We compare our space-based N₂O emissions estimates derived using California-observed N₂O:NO_x emission ratios with N₂O emissions from independent studies. We first compare N₂O emissions derived from TROPOMI-NO₂ observations with those obtained from chamber measurements reported by Lawrence et al., (2021). The chamber measurements, conducted between February 2017 and October 2019 in Iowa crop fields, are compared only for the warm season (May-September) of 2018 and 2019 when TROPOMI was operational, and chamber data was available. The comparison domain spans -94.055 to -93.305 in longitude (0.75°) and 41.605 to 42.355 in latitude (0.75°). The box model domain lies to the north of Des Moines, Iowa, and is centered on the Ames, Iowa field site referenced in Lawrence et al., (2021)(41.98°N, 93.68°W), and is shown in Fig. 2A, with a star indicating the chamber location.

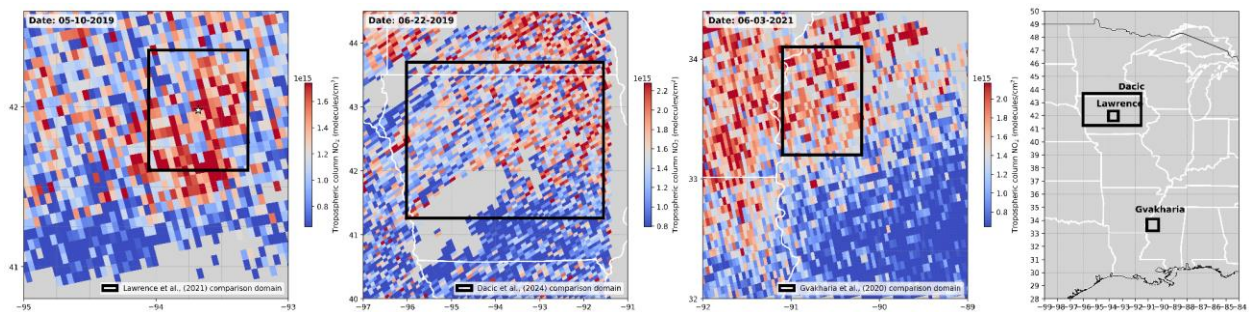
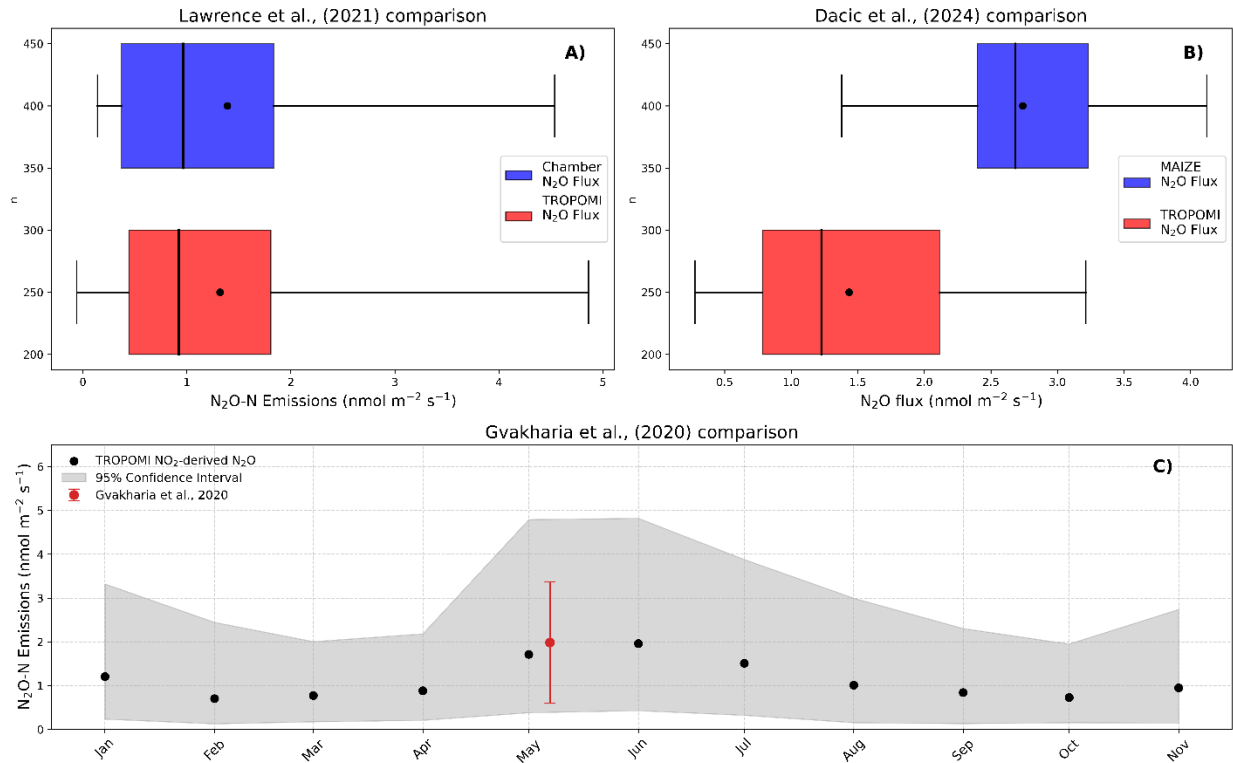


Figure 2: TROPOMI tropospheric NO₂ columns and the box model domains used for comparison with A) Lawrence et al., 2021 with a star denoting the chamber location, B) Dacic et al., 2024, and C) Gvakharia et al., 2020. D) Each corresponding region shown on a map of the central US.

We calculate the confidence interval for the Lawrence et al., (2021) chamber dataset by randomly sampling daily average values on days that we also have TROPOMI NO₂-derived N₂O estimates and calculating a 95th confidence interval. For the same observational time-window, we derive daily N₂O emission estimates for the box model domain using the proxy-method described in Sect. 4. The distribution of chamber-N₂O emissions and its associated 95% confidence interval against the mean and 95% confidence interval for TROPOMI NO₂-derived N₂O flux are shown in Fig. 3A.



290 **Figure 3: Satellite derived estimates concurrence with independent studies. (A, top left) Box plots of the distribution of daily average N₂O flux derived from chamber observations detailed in Lawrence et al., 2021 and TROPOMI observations from that period. (B, top right) Box plots of N₂O flux observed by TROPOMI across the MAIZE campaign domain, and ensemble averages for coincident days of the MAIZE (2021-2022) campaign. (C, Bottom) TROPOMI-NO₂ derived N₂O flux (gray distribution) compared against the N₂O flux estimate from Gvakharia et al., (2020) (red band).**

295 The confidence interval for the mean chamber-derived N₂O flux largely overlaps with that of the TROPOMI NO₂-derived N₂O flux (Fig. 3A). The mean values differ by ~4.5% (~7.3 % using *approach 1*), with the chamber-derived flux averaging 1.38 (0.14, 4.53; 95% CI) nmol N₂O/m²/s and the TROPOMI-derived flux averaging 1.32 (-0.06, 4.86; 95% CI) (1.48 (-0.06, 6.28; 95% CI) nmol N₂O/m²/s using *approach 1*). We evaluate the difference in these means with a nonparametric permutation test, which indicates the observed differences between population means are not significantly different. These are independent dataset and methods that operate on different scales. The relative agreement in mean values and the overlap in confidence intervals suggest that the TROPOMI-based

300 approach provides a reasonable estimate of long-term chamber-derived mean N₂O flux in this study.

Next, we compare TROPOMI NO₂-derived N₂O fluxes with N₂O emissions derived from aircraft observations during the Measurements of Agriculture Illuminating farm-Zone Emissions of N₂O (MAIZE) 2021 and 2022 campaigns (Dacic et al., 2024; Kort et al., 2022, 2024a, 2024b). These airborne campaigns measured N₂O concentrations over the Iowa croplands during May and June of both years. Observed N₂O concentrations were linked to the surface using an atmospheric transport model, and an ensemble of surface fluxes was derived using a Bayesian inversion framework. In this comparison, we use a larger analysis domain to match the area over which the MAIZE campaigns took place. For 5 flight days of the MAIZE campaign (2021-05-31, 2021-06-03, 2022-05-18, 2022-05-20, and 2022-05-21), we produce a TROPOMI NO₂-derived N₂O average flux for the MAIZE domain (S: 40.398; N: 43.399; W: -96.724; E: -90.044, Fig. 2B). We compare this with MAIZE daily ensemble averages. We then randomly sample the MAIZE daily flux ensembles using the previously described Monte Carlo resampling approach to obtain a 95% confidence interval for MAIZE N₂O flux. Figure 3B shows the comparison between airborne-informed MAIZE N₂O flux and N₂O flux we derive from TROPOMI NO₂ observations and our aircraft-derived emission ratios.

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While the mean TROPOMI-derived N₂O flux is within the 95% confidence interval of the MAIZE emissions, and vice versa (Fig 3B), there is less notable agreement than in the comparison with the chamber emissions from Lawrence et al., (2021) for a similar domain. There exist multiple possible reasons for the larger apparent discrepancy. 1) The comparison is limited to only five days. 2) The MAIZE aircraft flights captured a heavy-tail emissions distribution with small number of fields contributing substantially to total emissions. These high emissions events might be missed by chamber observations, and the coarse scale of the satellite observations used here might reduce sensitivity to small regions with high emissions, thus explaining the TROPOMI and chamber relative agreement with both values lower than determined by flights in MAIZE. 3) It is also possible the enhancement ratio approach used here is failing to capture the emissions ratio as well as desired for this place and time. Still, the mean emissions rate determined from satellite is captured within the airborne campaign 95% confidence interval, and thus it appears this space-based proxy approach can provide a reasonable mean estimate for this region with five days of observations.

Finally, we compare N₂O fluxes derived using the proposed space-based NO₂ proxy method to fluxes derived from airborne mass balance estimates from Gvakharia et al., (2020) over the Mississippi River Valley. During the Fertilizer Emissions Airborne Study (FEAST) in Spring 2017, Gvakharia et al., (2020) observed N₂O fluxes of 1.98 +/- 1.39 nmol N₂O-N/m²/s in May 2017, noting significant spatial variation. The TROPOMI instrument was not operational until late 2018, so we do not have overlapping data to directly compare TROPOMI NO₂-derived N₂O flux estimates with those from Gvakharia et al., (2020). Instead, we calculate emissions for a full calendar year for 2021 and compare these estimates with the May 2017 estimate from the FEAST data (see Fig. 2C and 3C). With the space-based proxy approach, we observe seasonal variation ranging from 0.75 nmol N₂O-N/m²/s in March (0.17, 2.0; 95% CI) (0.83 nmol N₂O-N/m²/s using *approach 1*) to a peak of 1.96 in June (0.43, 4.8; 95% CI) (2.22 nmol N₂O-N/m²/s using *approach 1*), and our spring estimate is in close agreement with the estimate from Gvakharia et al., (2020) is shown in Fig. 3C. Specifically, we estimate 1.72 nmol N₂O-N/m²/s in May (0.38, 4.8; 95% CI) (14.3% difference) (1.93 nmol N₂O-N/m²/s in May 2.4% difference using *approach 1*) using TROPOMI NO₂ observations from 2021.

We find the TROPOMI NO₂-derived N₂O flux compares favorably with various independent measures of N₂O flux and emissions from the corn belt (Dacic et al., 2024; Lawrence et al., 2021) and Mississippi River Valley (Gvakharia et al., 2020). For two of the comparisons, space-based estimates are within ~15% of these independently obtained N₂O estimates, despite this testing capturing multiple regions and time-periods, and the airborne derived emission ratios coming from observations in a completely different agricultural region. The N₂O:NO_x ratios used here were observed with aircraft over California croplands – very different from the rainfed agricultural regions in the Midwest and southern USA. Previous studies have demonstrated strong spatiotemporal variation in emission ratios in response to soil moisture (Anderson and Levine, 1987; Davidson, 1992; Johansson and Sanhueza, 1988; Lipschultz et al., 1981; Tortoso and Hutchinson, 1990) and crop variety (Anderson and Levine, 1987) and suggests in wetter regions N₂O:NO_x ratios would shift upward in general. If that pattern held at the scales observed here, one would expect the satellite method to produce an underestimate of Midwest and southern USA emissions, which is perhaps another explanation for the comparison between the satellite method and Dacic et al., (2024). The general agreement of our proxy-based N₂O estimates with those from independent assessments of cropland N₂O emissions demonstrates the potential of scaling satellite-based NO₂ observations with N₂O:NO_x emission ratios to capture agricultural N₂O emissions, and that such an approach may provide a viable method to estimate N₂O emissions from agricultural regions around the world without necessarily needing location specific N₂O:NO_x emission ratios. Further measurements of N₂O:NO_x emissions at commensurate spatial scales with satellite measurements across different agricultural regions over time would be invaluable to further evaluate this method's validity to capture emissions through potentially complex confounding spatial and temporal factors.

360 **6 Conclusion:**

Constraining global emissions of N₂O is crucial to understanding its spatiotemporal emission distribution, drivers of emissions, and to guide effective mitigation strategies. Ground-based measurements are inherently limited to the

365 regions where they are installed, while airborne methods are often limited to targeted, short-duration research
campaigns. North America has been the focus of many studies, but less is known about the other large agricultural
regions around the world. Satellite observations, thus, are an attractive option because they have the potential for
more spatial coverage (~global during the warm season) and relatively fine (~daily) temporal resolution. This can
also serve to bridge the gap that exists between the present point- and region-scale N₂O monitoring. In the absence
of direct space-based observations of surface N₂O concentrations, we propose to leverage the well-observed trace
gas NO₂ as a proxy for N₂O emissions to create a pathway to monitor N₂O emissions in global agricultural regions
370 more comprehensively.

In this work, we derive airborne N₂O-to-NO_x emission ratios from the CalNex (2010) airborne campaign around a
dense agricultural region of California. These ratios represent the molecular emissions ratio of N₂O to NO_x from
croplands at spatial scales commensurate with space-based NO₂ observations. We combine these ratios with
satellite-derived NO_x soil emissions to estimate N₂O emissions. We compare our TROPOMI NO₂-derived N₂O
375 fluxes with N₂O emissions estimates from independent chamber observations and two distinct airborne campaigns
made in Iowa and the Mississippi River Valley. Our space-based N₂O emissions estimates compare favorably with
these independent estimates across different regions and as measured by different methods covering different spatial
and temporal scales. In comparison with chamber-derived N₂O flux (Lawrence et al., 2021), our estimate of mean
flux only differs by 3.8% %, or ~0.12 nmol N₂O/m²/s. Mean estimates differ from airborne emission ratios taken in
380 the Mississippi River Valley (Gvakharia et al., 2020) by ~14.3% %. Comparing emissions derived from Bayesian
inversion of aircraft data (Dacic et al., 2024) yields a larger N₂O flux mean difference by ~60%. In all cases, the
confidence intervals of our space-based N₂O flux estimates and those from independent measurements and
approaches overlap.

We have demonstrated that space-based NO₂ observations as a proxy for N₂O cropland emissions compare
385 favorably to independent estimates across multiple agricultural areas and years. This suggests that space-based NO₂
retrievals are a viable and robust proxy for N₂O flux at scales of at least 0.75 x 0.75 degrees, and over timescales as
short as five days. Further development and refinement of approaches to characterize agricultural NO₂ from satellite
observations and link them to N₂O emissions are possible. As presented here, the largest source of uncertainty in the
estimated N₂O emissions derives from the large variability in the observed airborne N₂O:NO_x emissions ratio.
390 Improved understanding and definition of this ratio, and what controls variation, could improve the fidelity of this
proxy approach. This could be accomplished with airborne observations of NO_x and N₂O. Capturing different crops,
agricultural practices and environmental conditions would provide more insight into emissions ratios and best
practices on how to apply to independent satellite data in new domains. A complementary approach to the use of
direct atmospheric observations of cropland N₂O and NO_x in our proxy-based method would be to combine satellite-
395 based or ground-based estimates of soil moisture with a biogeochemical model, such as DayCent (Li et al., 1992;
Parton et al., 1998), to derive modeled N₂O:NO_x emission ratios. With such an approach one could model emissions,
and uncertainties, over many different regions and conditions where measurements may not be possible. The work
presented here demonstrates a proxy-based approach that may offer a path towards a more spatially comprehensive
constraint on regional and global budgets of agricultural N₂O emissions.

400 **Data Availability**

All data used in this manuscript are archived in public databases. Airborne data from P3 aircraft during the CalNex
campaign is available from the NOAA Chemical Sciences Laboratory at <https://csl.noaa.gov/projects/calnex/>.
TROPOMI Level 2 Nitrogen Dioxide total column products, Version 02, are available from the European Space
Agency at <https://doi.org/10.5270/S5P-9bnp8q8>. The National Emission Inventory is available from the
405 Environmental Protection Agency at [https://www.epa.gov/air-emissions-inventories/2017-national-emissions-](https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-data)
[inventory-nei-data](https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-data). Chamber flux measurements from Lawrence et al. (2021) are available
at <https://doi.org/10.6073/pasta/e6117972f6a80d5f5a9db354957910ed>. Airborne data from the FEAST campaign
and Gvakharia et al. (2020) is available at <https://doi.org/10.7302/Z2XK8CRG>. Posterior fluxes from the airborne
MAIZE campaign and Dacic et al. (2024) are available at <https://doi.org/10.7302/9w5m-mn30>.

410 **Author Contribution**

TA developed the box model code, conducted all model simulations, and designed and optimized the aircraft data filtering methods. TA also prepared the manuscript, with significant input from EK and GP. EK conceived the project idea. EK and GP provided guidance on methodology and the presentation of results, and contributed to data collection and modeling for the experimental datasets used for comparison.

415 **Competing Interest**

The authors declare no competing interest.

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References:

- 430 Acker, S., Holloway, T., & Harkey, M. (2025). Satellite detection of NO₂ distributions using TROPOMI and TEMPO and comparison with ground-based concentration measurements. *Atmospheric Chemistry and Physics*, 25(14), 8271–8288. <https://doi.org/10.5194/ACP-25-8271-2025>
- Adams, T. J., Geddes, J. A., and Lind, E. S.: New Insights Into the Role of Atmospheric Transport and Mixing on Column and Surface Concentrations of NO₂ at a Coastal Urban Site, *Journal of Geophysical Research: Atmospheres*, 128, e2022JD038237, <https://doi.org/10.1029/2022JD038237>, 2023.
- 435 Anderson, I. C. and Levine, J. S.: Simultaneous field measurements of biogenic emissions of nitric oxide and nitrous oxide., *J Geophys Res*, 92, 965–976, <https://doi.org/10.1029/JD092ID01P00965>, 1987.
- Baggs, E. M.: A review of stable isotope techniques for N₂O source partitioning in soils: recent progress, remaining challenges and future considerations, *Rapid Communications in Mass Spectrometry*, 22, 1664–1672, <https://doi.org/10.1002/RCM.3456>, 2008.
- 440 Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., and Zechmeister-Boltenstern, S.: Nitrous oxide emissions from soils: How well do we understand the processes and their controls, *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368, <https://doi.org/10.1098/RSTB.2013.0122>, 2013.
- Cardenas, L., Rondon, A., Johansson, C., and Sanhueza, E.: Effects of soil moisture, temperature, and inorganic nitrogen on nitric oxide emissions from acidic tropical savannah soils, *J Geophys Res*, 98, 14783–14790, <https://doi.org/10.1029/93JD01020>, 1993.
- 445 Chen, Y., Tessier, S., MacKenzie, A. F., and Laverdière, M. R.: Nitrous oxide emission from an agricultural soil subjected to different freeze-thaw cycles, *Agric Ecosyst Environ*, 55, 123–128, [https://doi.org/10.1016/0167-8809\(95\)00611-U](https://doi.org/10.1016/0167-8809(95)00611-U), 1995.
- 450 Chen, Z., Griffis, T. J., Millet, D. B., Wood, J. D., Lee, X., Baker, J. M., Xiao, K., Turner, P. A., Chen, M., Zobitz, J., and Wells, K. C.: Partitioning N₂O emissions within the U.S. Corn Belt using an inverse modeling approach, *Global Biogeochem Cycles*, 30, 1192–1205, <https://doi.org/10.1002/2015GB005313>, 2016.

- Copernicus Sentinel data processed by ESA, Koninklijk Nederlands Meteorologisch Instituut (KNMI), Sentinel-5P TROPOMI Tropospheric NO₂ 1-Orbit L2 5.5km x 3.5km, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed 2025/09/04, [10.5270/S5P-9bnp8q8](https://doi.org/10.5270/S5P-9bnp8q8), 2021
- 455 Dacic, N., Plant, G., and Kort, E. A.: Airborne Measurements Reveal High Spatiotemporal Variation and the Heavy-Tail Characteristic of Nitrous Oxide Emissions in Iowa, *Journal of Geophysical Research: Atmospheres*, 129, e2024JD041403, <https://doi.org/10.1029/2024JD041403>, 2024.
- Davidson, E. A.: Sources of Nitric Oxide and Nitrous Oxide following Wetting of Dry Soil, *Soil Science Society of America Journal*, 56, 95–102, <https://doi.org/10.2136/SSSAJ1992.03615995005600010015X>, 1992.
- 460 Davidson, E. A. and Kanter, D.: Inventories and scenarios of nitrous oxide emissions, *Environmental Research Letters*, 9, 105012, <https://doi.org/10.1088/1748-9326/9/10/105012>, 2014.
- 465 Davidson, E. A., Keller, M., Erickson, H. E., Verchot, L. V., and Veldkamp, E.: Testing a Conceptual Model of Soil Emissions of Nitrous and Nitric Oxides: Using two functions based on soil nitrogen availability and soil water content, the hole-in-the-pipe model characterizes a large fraction of the observed variation of nitric oxide and nitrous oxide emissions from soils, *Bioscience*, 50, 667–680, [https://doi.org/10.1641/0006-3568\(2000\)050\[0667:TACMOS\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2000)050[0667:TACMOS]2.0.CO;2), 2000.
- Desjardins, R., Rochette, P., Pattey, E., and MacPherson, I.: Measurements of greenhouse gas fluxes using aircraft- and tower-based techniques, *Agricultural Ecosystem Effects on Trace Gases and Global Climate Change*, 45–62, <https://doi.org/10.2134/ASASPECPUB55.C3>, 2015.
- 470 Eckl, M., Roiger, A., Kostinek, J., Fiehn, A., Huntrieser, H., Knote, C., Barkley, Z. R., Ogle, S. M., Baier, B. C., Sweeney, C., and Davis, K. J.: Quantifying Nitrous Oxide Emissions in the U.S. Midwest: A Top-Down Study Using High Resolution Airborne In-Situ Observations, *Geophys Res Lett*, 48, e2020GL091266, <https://doi.org/10.1029/2020GL091266>, 2021.
- 475 Van Geffen, J., Folkert Boersma, K., Eskes, H., Sneep, M., Ter Linden, M., Zara, M., and Pepijn Veeffkind, J.: S5P TROPOMI NO₂ slant column retrieval: Method, stability, uncertainties and comparisons with OMI, *Atmos Meas Tech*, 13, 1315–1335, <https://doi.org/10.5194/AMT-13-1315-2020>, 2020.
- Ghude, S. D., Lal, D. M., Beig, G., Van Der A, R., and Sable, D.: Rain-induced soil NO_x emission from India during the onset of the summer monsoon: A satellite perspective, *Journal of Geophysical Research Atmospheres*, 115, 16304, <https://doi.org/10.1029/2009JD013367>, 2010.
- 480 Goldberg, D. L., Lu, Z., Streets, D. G., De Foy, B., Griffin, D., McLinden, C. A., Lamsal, L. N., Krotkov, N. A., and Eskes, H.: Enhanced Capabilities of TROPOMI NO₂: Estimating NO_x from North American Cities and Power Plants, *Environ Sci Technol*, 53, 12594–12601, <https://doi.org/10.1021/ACS.EST.9B04488>, 2019a.
- 485 Goldberg, D. L., Lu, Z., Oda, T., Lamsal, L. N., Liu, F., Griffin, D., McLinden, C. A., Krotkov, N. A., Duncan, B. N., and Streets, D. G.: Exploiting OMI NO₂ satellite observations to infer fossil-fuel CO₂ emissions from U.S. megacities, *Science of The Total Environment*, 695, 133805, <https://doi.org/10.1016/J.SCITOTENV.2019.133805>, 2019b.
- Goldberg, D. L., Anenberg, S. C., Kerr, G. H., Mohegh, A., Lu, Z., and Streets, D. G.: TROPOMI NO₂ in the United States: A Detailed Look at the Annual Averages, Weekly Cycles, Effects of Temperature, and Correlation With Surface NO₂ Concentrations, *Earths Future*, 9, e2020EF001665, <https://doi.org/10.1029/2020EF001665>, 2021.
- 490 Goldberg, D. L., Tao, M., Kerr, G. H., Ma, S., Tong, D. Q., Fiore, A. M., Dickens, A. F., Adelman, Z. E., and Anenberg, S. C.: Evaluating the spatial patterns of U.S. urban NO_x emissions using TROPOMI NO₂, *Remote Sens Environ*, 300, 113917, <https://doi.org/10.1016/J.RSE.2023.113917>, 2024.
- Gonzalez Abad, G., Souri, A. H., Bak, J., Chance, K., Flynn, L. E., Krotkov, N. A., Lamsal, L., Li, C., Liu, X., Miller, C. C., Nowlan, C. R., Suleiman, R., and Wang, H.: Five decades observing Earth's atmospheric trace gases

- 495 using ultraviolet and visible backscatter solar radiation from space, *J Quant Spectrosc Radiat Transf*, 238, 106478, <https://doi.org/10.1016/J.QSRT.2019.04.030>, 2019.
- Griffis, T. J., Lee, X., Baker, J. M., Russelle, M. P., Zhang, X., Venterea, R., and Millet, D. B.: Reconciling the differences between top-down and bottom-up estimates of nitrous oxide emissions for the U.S. Corn Belt, *Global Biogeochem Cycles*, 27, 746–754, <https://doi.org/10.1002/GBC.20066>, 2013.
- 500 Gvakharia, A., Kort, E. A., Brandt, A., Peischl, J., Ryerson, T. B., Schwarz, J. P., Smith, M. L., and Sweeney, C.: Methane, Black Carbon, and Ethane Emissions from Natural Gas Flares in the Bakken Shale, North Dakota, *Environ Sci Technol*, 51, 5317–5325, <https://doi.org/10.1021/ACS.EST.6B05183>, 2017.
- Gvakharia, A., Kort, E. A., Smith, M. L., and Conley, S.: Evaluating Cropland N₂O Emissions and Fertilizer Plant Greenhouse Gas Emissions With Airborne Observations, *Journal of Geophysical Research: Atmospheres*, 125, e2020JD032815, <https://doi.org/10.1029/2020JD032815>, 2020.
- 505 Godłowska, J., Hajto, M. J., Lapeta, B., & Kaszowski, K. (2023). The attempt to estimate annual variability of NO_x emission in Poland using Sentinel-5P/TROPOMI data. *Atmospheric Environment*, 294, 119482. <https://doi.org/10.1016/J.ATMOSENV.2022.119482>
- Hanrahan, P. L. (1999). The Plume Volume Molar Ratio Method for Determining NO₂/NO_x Ratios in Modeling—Part I: Methodology. *Journal of the Air and Waste Management Association*, 49(11), 1324–1331. <https://doi.org/10.1080/10473289.1999.10463960;WGROU:STRING:PUBLICATION>
- 510 Harrison, R. M., Yamulki, S., Goulding, K. W. T., and Webster, C. P.: Effect of fertilizer application on NO and N₂O fluxes from agricultural fields, *J Geophys Res*, 100, 25923–25931, <https://doi.org/10.1029/95JD02461>, 1995.
- Herrera, S. A., Diskin, G. S., Harward, C., Sachse, G., De Wekker, S. F. J., Yang, M., Choi, Y., Wisthaler, A., Mallia, D. V., and Pusede, S. E.: Wintertime Nitrous Oxide Emissions in the San Joaquin Valley of California Estimated from Aircraft Observations, *Environ Sci Technol*, 55, 4462–4473, <https://doi.org/10.1021/ACS.EST.0C08418>, 2021.
- 515 Huber, D. E., Steiner, A. L., and Kort, E. A.: Daily Cropland Soil NO_x Emissions Identified by TROPOMI and SMAP, *Geophys Res Lett*, 47, e2020GL089949, <https://doi.org/10.1029/2020GL089949>, 2020.
- Huber, D. E., Kort, E. A., and Steiner, A. L.: Soil Moisture, Soil NO_x and Regional Air Quality in the Agricultural Central United States, *Journal of Geophysical Research: Atmospheres*, 129, e2024JD041015, <https://doi.org/10.1029/2024JD041015>, 2024.
- 520 Ialongo, I., Virta, H., Eskes, H., Hovila, J., and Douros, J.: Comparison of TROPOMI/Sentinel-5 Precursor NO₂ observations with ground-based measurements in Helsinki, *Atmos Meas Tech*, 13, 205–218, <https://doi.org/10.5194/AMT-13-205-2020>, 2020.
- 525 Jacob, D. J.: Introduction to Atmospheric Chemistry, *Introduction to Atmospheric Chemistry*, 1–280, 1999.
- Jaeglé, L., Martin, R. V., Chance, K., Steinberger, L., Kurosu, T. P., Jacob, D. J., Modi, A. I., Yoboué, V., Sigha-Nkamdjou, L., and Galy-Lacaux, C.: Satellite mapping of rain-induced nitric oxide emissions from soils, *Journal of Geophysical Research: Atmospheres*, 109, 21310, <https://doi.org/10.1029/2004JD004787>, 2004.
- 530 Jimenez, R., Herndon, S., Shorter, J. H., Nelson, D. D., McManus, J. B., and Zahniser, M. S.: Atmospheric trace gas measurements using a dual quantum-cascade laser mid-infrared absorption spectrometer, <https://doi.org/10.1117/12.597130>, 2005.
- Johansson, C.: Field measurements of emission of nitric oxide from fertilized and unfertilized forest soils in Sweden, *J Atmos Chem*, 1, 429–442, <https://doi.org/10.1007/BF00053804>, 1984.
- 535 Johansson, C. and Sanhueza, E.: Emission of NO from savanna soils during rainy season, *Journal of Geophysical Research: Atmospheres*, 93, 14193–14198, <https://doi.org/10.1029/JD093ID11P14193>, 1988.

- Kim, D. G., Vargas, R., Bond-Lamberty, B., and Turetsky, M. R.: Effects of soil rewetting and thawing on soil gas fluxes: A review of current literature and suggestions for future research, *Biogeosciences*, 9, 2459–2483, <https://doi.org/10.5194/BG-9-2459-2012>, 2012.
- 540 Kimbrough, S., Chris Owen, R., Snyder, M., & Richmond-Bryant, J. (2017). NO to NO₂ Conversion Rate Analysis and Implications for Dispersion Model Chemistry Methods using Las Vegas, Nevada Near-Road Field Measurements. *Atmospheric Environment* (Oxford, England : 1994), 165, 23. <https://doi.org/10.1016/J.ATMOSENV.2017.06.027>
- 545 Kort, E. A., Eluszkiewicz, J., Stephens, B. B., Miller, J. B., Gerbig, C., Nehrkorn, T., Daube, B. C., Kaplan, J. O., Houweling, S., and Wofsy, S. C.: Emissions of CH₄ and N₂O over the United States and Canada based on a receptor-oriented modeling framework and COBRA-NA atmospheric observations, *Geophys Res Lett*, 35, <https://doi.org/10.1029/2008GL034031>, 2008.
- Kort, E. A., Patra, P. K., Ishijima, K., Daube, B. C., Jiménez, R., Elkins, J., Hurst, D., Moore, F. L., Sweeney, C., and Wofsy, S. C.: Tropospheric distribution and variability of N₂O: Evidence for strong tropical emissions, *Geophys Res Lett*, 38, <https://doi.org/10.1029/2011GL047612>, 2011.
- 550 Kort, E. A., Plant, G., Dacic, N. *Aircraft Data (2021) for Measurement of Agriculture Illuminating farm-Zone Emissions of N₂O (MAIZE)*, University of Michigan - Deep Blue Data. <https://doi.org/10.7302/0jvh-0c91>, 2022
- Kort, E. A., Plant, G., Dacic, N. *Aircraft Data (2022) for Measurement of Agriculture Illuminating farm-Zone Emissions of N₂O (MAIZE)*, University of Michigan - Deep Blue Data. <https://doi.org/10.7302/tmfd-nw87>, 2024
- 555 Kort, E. A., Plant, G., Dacic, N. *Posterior Flux Ensemble for Measurement of Agriculture Illuminating farm-Zone Emissions of N₂O (MAIZE)*, University of Michigan - Deep Blue Data. <https://doi.org/10.7302/9w5m-mn30>, 2024
- Lawrence, N. C., Tenesaca, C. G., VanLoocke, A., and Hall, S. J.: Nitrous oxide emissions from agricultural soils challenge climate sustainability in the US Corn Belt, *Proc Natl Acad Sci U S A*, 118, e2112108118, <https://doi.org/10.1073/PNAS.2112108118>, 2021.
- 560 Levine, J. S., Winstead, E. L., Parsons, D. A. B., Scholes, M. C., Scholes, R. J., Cofer, W. R., Cahoon, D. R., and Sebacher, D. I.: Biogenic soil emissions of nitric oxide (NO) and nitrous oxide (N₂O) from savannas in South Africa: The impact of wetting and burning, *Journal of Geophysical Research: Atmospheres*, 101, 23689–23697, <https://doi.org/10.1029/96JD01661>, 1996.
- Changsheng Li, Frolking, S., & Frolking, T. A. (1992). A model of nitrous oxide evolution from soil driven by rainfall events: 2. Model applications. *Journal of Geophysical Research*, 97(D9), 9777–9783. <https://doi.org/10.1029/92jd00510>
- 565 Li, M., McDonald, B. C., McKeen, S. A., Eskes, H., Levelt, P., Francoeur, C., Harkins, C., He, J., Barth, M., Henze, D. K., Bela, M. M., Trainer, M., de Gouw, J. A., & Frost, G. J. (2021). Assessment of Updated Fuel-Based Emissions Inventories Over the Contiguous United States Using TROPOMI NO₂ Retrievals. *Journal of Geophysical Research: Atmospheres*, 126(24), e2021JD035484. <https://doi.org/10.1029/2021JD035484>
- 570 Liang, Q., Nevison, C., Dlugokencky, E., Hall, B. D., and Dutton, G.: 3-D Atmospheric Modeling of the Global Budget of N₂O and Its Isotopologues for 1980–2019: The Impact of Anthropogenic Emissions, *Global Biogeochem Cycles*, 36, e2021GB007202, <https://doi.org/10.1029/2021GB007202>, 2022.
- 575 Lin, X., van der A, R. J., de Laat, J., Huijnen, V., Mijling, B., Ding, J., Eskes, H., Douros, J., Liu, M., Zhang, X., Liu, Z., van der, R. A., and Liu avander, Z.: European soil NO_x emissions derived from satellite NO₂ observations, *Authorea Preprints*, <https://doi.org/10.22541/ESSOAR.170224578.81570487/V1>, 2023.
- Lipschultz, F., Zafiriou, O. C., Wofsy, S. C., McElroy, M. B., Valois, F. W., and Watson, S. W.: Production of NO and N₂O by soil nitrifying bacteria, *Nature*, 294, 641–643, <https://doi.org/10.1038/294641A0>, 1981.

- 580 Liu, S., Lin, F., Wu, S., Ji, C., Sun, Y., Jin, Y., Li, S., Li, Z., and Zou, J.: A meta-analysis of fertilizer-induced soil NO and combined NO+N₂O emissions, *Glob Chang Biol*, 23, 2520–2532, <https://doi.org/10.1111/GCB.13485>, 2017.
- di Marco, C., Skiba, U., Weston, K., Hargreaves, K., and Fowler, D.: Field scale N₂O flux measurements from grassland using eddy covariance, *Water, Air, & Soil Pollution: Focus* 2004 4:6, 4, 143–149, <https://doi.org/10.1007/S11267-005-3024-X>, 2005.
- 585 Merlos, F. A. and Hijmans, R. J.: The scale dependency of spatial crop species diversity and its relation to temporal diversity, *Proc Natl Acad Sci U S A*, 117, 26176–26182, <https://doi.org/10.1073/PNAS.2011702117>, 2020.
- Müller, C., Kammann, C., Ottow, J. C. G., and Jäger, H. J.: Nitrous oxide emission from frozen grassland soil and during thawing periods, *Journal of Plant Nutrition and Soil Science*, 166, 46–53, <https://doi.org/10.1002/JPLN.200390011>, 2003.
- 590 Nevison, C., Andrews, A., Thoning, K., Dlugokencky, E., Sweeney, C., Miller, S., Saikawa, E., Benmergui, J., Fischer, M., Mountain, M., and Nehrkorn, T.: Nitrous Oxide Emissions Estimated With the CarbonTracker-Lagrange North American Regional Inversion Framework, *Global Biogeochem Cycles*, 32, 463–485, <https://doi.org/10.1002/2017GB005759>, 2018.
- 595 Nevison, C., Lan, X., and Ogle, S. M.: Remote Sensing Soil Freeze-Thaw Status and North American N₂O Emissions From a Regional Inversion, *Global Biogeochem Cycles*, 37, e2023GB007759, <https://doi.org/10.1029/2023GB007759>, 2023.
- Oikawa, P. Y., Ge, C., Wang, J., Eberwein, J. R., Liang, L. L., Allsman, L. A., Grantz, D. A., and Jenerette, G. D.: Unusually high soil nitrogen oxide emissions influence air quality in a high-temperature agricultural region, *Nat Commun*, 6, 1–10, <https://doi.org/10.1038/NCOMMS9753>, 2015.
- 600 Park, J. U., Park, J. S., Diaz, D. S., Gebetsberger, M., Müller, M., Shalaby, L., Tiefengraber, M., Kim, H. J., Park, S. S., Song, C. K., and Kim, S. W.: Spatiotemporal inhomogeneity of total column NO₂ in a polluted urban area inferred from TROPOMI and Pandora intercomparisons, *GIsci Remote Sens*, 59, 354–373, <https://doi.org/10.1080/15481603.2022.2026640>, 2022.
- 605 Parton, W. J., Hartman, M., Ojima, D., & Schimel, D. (1998). DAYCENT and its land surface submodel: description and testing. *Global and Planetary Change*, 19(1–4), 35–48. [https://doi.org/10.1016/S0921-8181\(98\)00040-X](https://doi.org/10.1016/S0921-8181(98)00040-X)
- Pilegaard, K. (2013). Processes regulating nitric oxide emissions from soils. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368(1621), 20130126. <https://doi.org/10.1098/RSTB.2013.0126/22212>
- 610 Pollack, I. B., Lerner, B. M., and Ryerson, T. B.: Evaluation of ultraviolet light-emitting diodes for detection of atmospheric NO₂ by photolysis - Chemiluminescence, *J Atmos Chem*, 65, 111–125, <https://doi.org/10.1007/S10874-011-9184-3>, 2010.
- Ravishankara, A. R., Daniel, J. S., and Portmann, R. W.: Nitrous oxide (N₂O): The dominant ozone-depleting substance emitted in the 21st century, *Science* (1979), 326, 123–125, <https://doi.org/10.1126/SCIENCE.1176985>, 2009.
- 615 Rowlings, D. W., Grace, P. R., Scheer, C., and Liu, S.: Rainfall variability drives interannual variation in N₂O emissions from a humid, subtropical pasture, *Science of The Total Environment*, 512–513, 8–18, <https://doi.org/10.1016/J.SCITOTENV.2015.01.011>, 2015.
- Ryerson, T. B., Huey, L. G., Knapp, K., Neuman, J. A., Parrish, D. D., Sueper, D. T., and Fehsenfeld, F. C.: Design and initial characterization of an inlet for gas-phase NO_y measurements from aircraft, *Journal of Geophysical Research: Atmospheres*, 104, 5483–5492, <https://doi.org/10.1029/1998JD100087>, 1999.

- 620 Ryerson, T. B., Trainer, M., Holloway, J. S., Parrish, D. D., Huey, L. G., Sueper, D. T., Frost, G. J., Donnelly, S. G., Schauffler, S., Atlas, E. L., Kuster, W. C., Goldan, P. D., Hübler, G., Meagher, J. F., and Fehsenfeld, F. C.: Observations of ozone formation in power plant plumes and implications for ozone control strategies, *Science* (1979), 292, 719–723, <https://doi.org/10.1126/SCIENCE.1058113>, 2001.
- 625 Ryerson, T. B., Trainer, M., Angevine, W. M., Brock, C. A., Dissly, R. W., Fehsenfeld, F. C., Frost, G. J., Goldan, P. D., Holloway, J. S., Hübler, G., Jakoubek, R. O., Kuster, W. C., Neuman, J. A., Nicks, D. K., Parrish, D. D., Roberts, J. M., Sueper, D. T., Atlas, E. L., Donnelly, S. G., Flocke, F., Fried, A., Potter, W. T., Schauffler, S., Stroud, V., Weinheimer, A. J., Wert, B. P., Wiedinmyer, C., Alvarez, R. J., Banta, R. M., Darby, L. S., and Senff, C. J.: Effect of petrochemical industrial emissions of reactive alkenes and NO_x on tropospheric ozone formation in Houston, Texas, *Journal of Geophysical Research: Atmospheres*, 108, 4249, <https://doi.org/10.1029/2002JD003070>, 2003.
- 630 Sanhueza, E., Wei Min Hao, Scharffe, D., Donoso, L., and Crutzen, P. J.: N₂O and NO emissions from soils of the northern part of the Guayana Shield, Venezuela, *J Geophys Res*, 95, 22481–22488, <https://doi.org/10.1029/JD095ID13P22481>, 1990.
- 635 Scholes, M. C., Martin, R., Scholes, R. J., Parsons, D., and Winstead, E.: NO and N₂O emissions from savanna soils following the first simulated rains of the season, *Nutr Cycl Agroecosyst*, 48, 115–122, <https://doi.org/10.1023/A:1009781420199>, 1997.
- Shepherd, M. F., Barzetti, S., and Hastie, D. R.: The production of atmospheric NO_x and N₂O from a fertilized agricultural soil, *Atmospheric Environment. Part A. General Topics*, 25, 1961–1969, [https://doi.org/10.1016/0960-1686\(91\)90277-E](https://doi.org/10.1016/0960-1686(91)90277-E), 1991.
- 640 Sihi, D., Davidson, E. A., Savage, K. E., and Liang, D.: Simultaneous numerical representation of soil microsite production and consumption of carbon dioxide, methane, and nitrous oxide using probability distribution functions, *Glob Chang Biol*, 26, 200–218, <https://doi.org/10.1111/GCB.14855>, 2020.
- Skiba, U., Smith, K. A., and fowler, D.: Nitrification and denitrification as sources of nitric oxide and nitrous oxide in a sandy loam soil, *Soil Biol Biochem*, 25, 1527–1536, [https://doi.org/10.1016/0038-0717\(93\)90007-X](https://doi.org/10.1016/0038-0717(93)90007-X), 1993.
- 645 Smith, K. A., McTaggart, I. P., and Tsuruta, H.: Emissions of N₂O and NO associated with nitrogen fertilization in intensive agriculture, and the potential for mitigation, *Soil Use Manag*, 13, 296–304, <https://doi.org/10.1111/J.1475-2743.1997.TB00601.X>, 1997.
- Strum, M., Eyth, A., and Vukovich, J.: Preparation of Emissions Inventories for the Version 7, 2014 Emissions Modeling Platform for NATA, 2017.
- 650 Tian, H., Xu, R., Canadell, J. G., Thompson, R. L., Winiwarter, W., Suntharalingam, P., Davidson, E. A., Ciais, P., Jackson, R. B., Janssens-Maenhout, G., Prather, M. J., Regnier, P., Pan, N., Pan, S., Peters, G. P., Shi, H., Tubiello, F. N., Zaehle, S., Zhou, F., Armeth, A., Battaglia, G., Berthet, S., Bopp, L., Bouwman, A. F., Buitenhuis, E. T., Chang, J., Chipperfield, M. P., Dangal, S. R. S., Dlugokencky, E., Elkins, J. W., Eyre, B. D., Fu, B., Hall, B., Ito, A., Joos, F., Krummel, P. B., Landolfi, A., Laruelle, G. G., Lauerwald, R., Li, W., Lienert, S., Maavara, T., MacLeod, M., Millet, D. B., Olin, S., Patra, P. K., Prinn, R. G., Raymond, P. A., Ruiz, D. J., van der Werf, G. R., Vuichard, N., Wang, J., Weiss, R. F., Wells, K. C., Wilson, C., Yang, J., and Yao, Y.: A comprehensive quantification of global nitrous oxide sources and sinks, *Nature*, 586, 248–256, <https://doi.org/10.1038/S41586-020-2780-0>, 2020.
- 655 Tian, H., Pan, N., Thompson, R. L., Canadell, J. G., Suntharalingam, P., Regnier, P., Davidson, E. A., Prather, M., Ciais, P., Muntean, M., Pan, S., Winiwarter, W., Zaehle, S., Zhou, F., Jackson, R. B., Bange, H. W., Berthet, S., Bian, Z., Bianchi, D., Bouwman, A. F., Buitenhuis, E. T., Dutton, G., Hu, M., Ito, A., Jain, A. K., Jeltsch-Thömmes, A., Joos, F., Kou-Giesbrecht, S., Krummel, P. B., Lan, X., Landolfi, A., Lauerwald, R., Li, Y., Lu, C., Maavara, T., Manizza, M., Millet, D. B., Mühle, J., Patra, P. K., Peters, G. P., Qin, X., Raymond, P., Resplandy, L., Rosentreter, J. A., Shi, H., Sun, Q., Tonina, D., Tubiello, F. N., Van Der Werf, G. R., Vuichard, N., Wang, J., Wells, K. C.,

- 665 Western, L. M., Wilson, C., Yang, J., Yao, Y., You, Y., and Zhu, Q.: Global nitrous oxide budget (1980-2020), *Earth Syst Sci Data*, 16, 2543–2604, <https://doi.org/10.5194/ESSD-16-2543-2024>, 2024.
- Williams, E. J., Hutchinson, G. L., & Fehsenfeld, F. C. (1992). NO_x And N₂O Emissions From Soil. *Global Biogeochemical Cycles*, 6(4), 351–388. <https://doi.org/10.1029/92GB02124>;WGROU:STRING:PUBLICATION
- Tortoso, A. C. and Hutchinson, G. L.: Contributions of autotrophic and heterotrophic nitrifiers to soil NO and N₂O emissions, *Appl Environ Microbiol*, 56, 1799–1805, <https://doi.org/10.1128/AEM.56.6.1799-1805.1990>, 1990.
- 670 Xiang, B., Miller, S. M., Kort, E. A., Santoni, G. W., Daube, B. C., Commane, R., Angevine, W. M., Ryerson, T. B., Trainer, M. K., Andrews, A. E., Nehrkorn, T., Tian, H., and Wofsy, S. C.: Nitrous oxide (N₂O) emissions from California based on 2010 CalNex airborne measurements, *Journal of Geophysical Research: Atmospheres*, 118, 2809–2820, <https://doi.org/10.1002/JGRD.50189>, 2013.
- 675 Yang, R., Hayashi, K., Zhu, B., Li, F., and Yan, X.: Atmospheric NH₃ and NO₂ concentration and nitrogen deposition in an agricultural catchment of Eastern China, *Science of The Total Environment*, 408, 4624–4632, <https://doi.org/10.1016/J.SCITOTENV.2010.06.006>, 2010.
- Zannetti, P., Van, Reinhold, N., and York, N.: *Air Pollution Modeling Theories, Computational Methods, Computational Mechanics Publications Southampton Boston*, 2013