Review

Extent and Variation of Nitrogen Losses from Non-legume Field Crops of Conterminous United States

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Abstract: Nitrogen (N) losses from field crops have raised environmental concerns. This manuscript accompanies a database of N loss studies from non-legume field crops conducted across the conterminous United States. Cumulative N losses through nitrous oxide-denitrification (CN₂O), ammonia volatilization (CNH₃), and nitrate leaching (CNO₃⁻) during the growing season and associated crop, soil, and water management information were gathered to determine the extent and controls of these losses. This database consisted of 404, 26, and 358 observations of CN₂O, CNH₃, and CNO₃⁻ losses, respectively, from sixty-two peer-reviewed manuscripts. Corn (Zea mays) dominated the N loss studies. Losses ranged between −0.04 to 16.9, 2.50 to 50.9, and 0 to 257 kg N ha⁻¹ for CN₂O, CNH₃ and CNO₃⁻, respectively. Most CN₂O and CNO₃⁻ observations were reported from Colorado (n = 100) and Iowa (n = 176), respectively. The highest values of CN₂O, and CNO₃⁻ were reported from Illinois and Minnesota states, and corn and potato (Solanum tuberosum), respectively. The application of anhydrous NH₃ had the highest value of CN₂O loss, and ammonium nitrate had the highest CNO₃⁻ loss. Among the different placement methods, the injection of fertilizer-N had the highest CN₂O loss, whereas the banding of fertilizer-N had the highest CNO₃⁻ loss. The maximum CNO₃⁻ loss was higher for chisel than no-tillage practice. Both CN₂O and CNO₃⁻ were positively correlated with fertilizer N application rate and the amount of water input (irrigation and rainfall). Fertilizer-N management strategies to control N loss should consider the spatio-temporal variability of interactions among climate, crop-and soil types.

Keywords: cumulative flux; denitrification; leaching; volatilization; irrigation; subsurface drainage; tillage

1. Introduction

Agricultural landscapes contribute to nitrate (NO₃⁻) leaching and gases like ammonia (NH₃) and nitrous oxide (N₂O) from denitrification [1,2]. Releases of these reactive N compounds link to adverse impacts on air, land, and water [3,4]. Since the 1970s, researchers initiated an effort to determine the consequences of fertilizer-N management practices on N losses through denitrification [5], leaching [6], and volatilization [7]. Worldwide cereal N use efficiency (NUE) was estimated to be approximately 33% [8], and somewhat higher efficiencies (37%) was estimated for corn in the US Corn belt [9]. Across the US, NUE generally decreased during 1987–2012, mainly due to increased use in mineral fertilizer N beyond crop requirements [10]. Annual fertilizer N application rate had increased from 0.22 g N m⁻² yr⁻¹ in 1940 to 9.04 g N m⁻² yr⁻¹ in 2015 [11]. Over the century, hotspots for N fertilizer use shifted from the southeastern and eastern to the Midwestern US, the Great Plains, and the Northwest [11]. In the Midwestern US, in low yielding years, overfertilization of low yield areas costs growers approximately USD 485 million per year in unused fertilizer N lost to the environment [12].
Global estimates suggest approximate N losses of 0.5–2%, 10–18%, and 10–20% of the fertilizer N input through denitrification, volatilization, and leaching, respectively [1,13–15]. The N cycle is complex, and substantial regional variability exists in reactive N formation and its degree of distribution. Regional scale drivers have substantial effects on N2O emissions and NO−3 leaching losses that conform and potentially exceed effects of fertilizer application rate [2]. In the Midwestern US, annual average N losses from stable high yield corn growing areas were averaged at only 51 kg N ha−1, whereas, estimated average N losses from stable low yield areas were 83 kg N ha−1, and unstable areas had intermediate N losses of 63 kg N ha−1 [12]. Control of particular N loss by specific factor varies with changes in other farm management decisions [16]. For example, no-till practice might be used to reduce N2O loss under irrigated condition but not under rainfed system [17]. Setting the research priorities and solutions to the problem of agricultural N loss requires a quantitative understanding of current N losses and controls of climate, soil, and plant interactions [4,9].

Agricultural N2O emissions were closely associated with fertilizer N source and rate, crop type, soil organic carbon (SOC) content, soil pH and texture [18]. Earlier, researchers [5] suggested that average background N2O emission from cultivated soils were 1.0 kg N2O-N ha−1 yr−1 within an additional increase of 1.25% of applied fertilizer-N in 90% of studies. However, recent studies have reported further fine control on the magnitude of N2O emission. A recent meta-analyses study had concluded an equivalent N2O release with 1 °C rise in average July temperature, and increase in soil C by 10 g kg−1 across North America [2]. The largest spike in N2O emissions was observed after a precipitation event greater than 20 mm [19]. Modification of the fertilizer-N rate, source, placement and/or timing has been recognized as an effective way to reduce N2O emissions [20,21]. However, the magnitude of the effect of N source varied spatially. Enhanced efficiency fertilizers like environmentally smart N or ESN (Nutrien Ltd., Saskatoon, SK, Canada) were not effective means to reduce N2O emission in a rainfed system, particularly under inconsistent rainfall [22]. The split application of urea to match the period of high crop N demand does not necessarily reduce, and may increase, N2O emission [23]. Fertilizer N management practices interact with other crop, soil and water management decisions. Tillage affected N2O emission in 2 out of 3 y, when emissions decreased in the order of moldboard plow > chisel plow > strip till > no-till for continuous corn production in Indiana [24]. Crop rotation and N rate had a greater effect than tillage system on N2O emission, in Colorado river basin [17].

Precipitation cycles of wet and dry years and soil organic matter (SOM) mineralization primarily control NO−3− concentration and loadings in subsurface drainage waters [25,26]. An additional 100 mm of precipitation can increase NO3− leaching losses from 8 to 9 kg N ha−1 [2]. Leaching loss reduced to 46% by the variable scheduling of irrigation (deficit calculation based on the crop growth stage) rather than a fixed deficit schedule (at 95% of maximum yield N rate) irrigation [27]. The amount of NO−3-N leaching increased linearly as the proportion of N applied at planting increased for the potato loamy sand at Becker, Minnesota [28]. To reduce the average NO3− concentration to less than 10 mg L−1 in subsurface drainage, it was estimated that N application rates would need to be less than 112 kg N ha−1 under corn-soybean rotation in Iowa soils [29]. Corn and soybean both have similar leaching potentials [30,31]; 54% of NO3− were lost in corn phase and 46% during soybean [32]. Fertilizer application timing and inhibitor addition can influence NO3− concentration [27]. Researchers found that NO3− concentration and loss followed the order: fall N > split N > spring N = fall N + nitrapyrin [33].

Nitrogen from fertilizers containing ammonia-based form, urea [CO(NH2)2], and ammonium sulfate [(NH4)2SO4] have the potential for volatilization loss [1]. Changes in the magnitude of volatilization can occur on a daily as well as seasonal basis. Urea hydrolysis rate and NH3 emission rate follow a diurnal sequence with a peak at the time of highest air temperature [34]. Conditions like the surface application of N-fertilizer without incorporation, alkaline soils (pH > 8.5) and dry condition can accelerate the volatilization loss. Surface-applied urea is hydrolyzed by the urease enzyme, resulting in a soil pH from 7 to 9 [35]. According to global synthesis, the use of non-urea-based fertilizers, deep placement of fertilizers and irrigation reduced NH3 volatilization by 75%, 55% and 35%, respectively [1].
The addition of urease inhibitors, for example, n-butyl phosphoric triamide (NBPT) has the potential to reduce the volatilization loss by 52% compared to urea without NBPT [36].

Main goal of this manuscript was to prepare the dataset of cumulative N losses. Peer-reviewed journal articles, reporting cumulative losses of denitrification, leaching, and volatilization during the growing season from non-leguminous crops in response to inorganic N fertilizer applications conducted in the conterminous United States. The dataset was studied and analyzed to determine the extent of N losses as influenced by (i) state, (ii) fertilizer-N management practices (source, application rate and time), (iii) main crop and previous crop in rotation, (iv) tillage practices, (v) water management (rainfed, irrigated and subsurface drainage), and (vi) soil properties (pH, texture, cation exchange capacity and SOM content). Correlation and regression of these factors with N losses were determined to understand the control of these factors.

2. Materials and Methods

2.1. Data Compilation

Peer-reviewed journal articles were collected, reporting field studies conducted in conterminous United States, reporting cumulative N losses (CN₂O, CNO⁻, and CNH₃) through July 2019 using Google Scholar (Google Inc., Mountain View, CA, USA) database. The keywords, ‘denitrification’, ‘leaching’ and ‘volatilization’, ‘corn’, ‘wheat’, ‘rice’, ‘crops’, were used for the search. Recent meta-analyses [1,2,36] were also checked to confirm the comprehensive inclusion of references. Studies reporting cumulative N losses of individual growing season from the specific fertilizer-N treatment were considered, but studies reporting organic N treatments, the average of multiple growing seasons or treatments or rotation were excluded. The final database was generated from sixty-two peer reviewed journal articles (Table 1 and Supplementary Materials).

From these journal articles, the following data and information were collected and arranged in separate columns: (i) location (region/field site), (ii) state, (iii) growing year, (iv) soil texture, (v) main crop, (vi) previous crop, (vii) tillage practice, (viii) water management (rainfed/subsurface-drained/irrigated), (ix) fertilizer N source, (x) amount of fertilizer-N applied (kg N ha⁻¹), (xi) application time, (xii) fertilizer placement, (xiii), cumulative N loss type and amount of N loss (kg N ha⁻¹), (xiv) crop yield (Mg ha⁻¹), (xv) amount of water input (growing season rainfall and irrigation), (xvi) soil pH, (xvii) cation exchange capacity (CEC) (centimole⁺ kg⁻¹), (xviii) sand content (g kg⁻¹), (xix) silt content (g kg⁻¹), (xx) clay content (g kg⁻¹), and (xxi) soil organic matter content (g kg⁻¹), see supplemental files for the database (database.xlsx) and list of references (references.docx). In the case of the absence of these values in the main manuscript, values were retrieved from other published journal articles associated with the experiment. Numerical data were collected from tables and graphs; data were extracted from figures using the WebplotDigitizer 4.2 software (https://automeris.io/WebPlotDigitizer).
Table 1. Nitrogen loss studies collected in the databases, their location, crop-, soil-, and water management, and soil characteristics.

| Citation                          | State | Crop             | Texture                        | Tillage | Soil pH | Water Mgmt. | N Losses Monitored |
|-----------------------------------|-------|------------------|--------------------------------|---------|---------|-------------|--------------------|
| Adviento-Borbe et al., 2007       | NE    | Corn             | Silty clay loam                | CP      | 6.14    | Irrigated   | N₂O               |
| Adviento-Borbe et al., 2013       | CA, AR| Rice             | Clay loam, Clay, Silt loam    | CP      | 5.46–6.19| Irrigated   | N₂O               |
| Bakhsh et al., 2002               | IA    | Corn             | Loam                           | CP, NT  | Unk     | Rainfed/Tile | NO₃               |
| Bakhsh et al., 2007               | IA    | Corn             | Loam                           | CP      | Unk     | Rainfed/Tile | NO₃               |
| Bakhsh et al., 2010               | IA    | Corn             | Loam                           | CP      | 5.5     | Rainfed/Tile | NO₃               |
| Basso and Ritchie 2005            | MI    | Corn             | Loam                           | CP      | 7.2     | Irrigated   | N₂O               |
| Bronson et al., 1992              | CO    | Corn             | Clay loam                      | CP      | 5.46    | Rainfed/Tile | NO₃               |
| Curtis et al., 2014               | PA    | Corn             | Silt loam                      | NT      | Unk     | Rainfed     | NO₃               |
| Duxbury and McConnaughhey 1986    | NY    | Corn             | Silt loam                      | Unk     | 6.9     | Unk         | N₂O               |
| Engel et al., 2017                | MT    | Winter wheat     | Clay loam                      | NT      | 6.3, 7.3| Rainfed     | NH₃               |
| Errebhi et al., 1998              | MN    | Potato           | Loamy sand                     | CP      | 6.7     | Irrigated   | N₂O               |
| Fernandez et al., 2015            | IL    | Corn             | Silt loam, Silty clay loam     | CP      | 6.2     | Rainfed/Tile | N₂O               |
| Fujinuma et al., 2011             | MN    | Corn             | Loamy sand                     | CP      | 4.85    | Irrigated   | N₂O               |
| Graham et al., 2018               | IL    | Corn             | Silt loam Silty clay loam      | CP      | 6.3, 6.1| Rainfed     | N₂O               |
| Guillard et al., 1999             | CT    | Corn             | Sandy loam                     | CP      | Unk     | Rainfed/Tile | NO₃               |
| Halvarson et al., 2008            | CO    | Corn, barley, dry bean | Clay loam | CP, NT  | 7.7–7.8 | Irrigated   | N₂O               |
| Halvarson and Delgrosso 2012      | CO    | Corn             | Clay loam                      | NT      | 7.6     | Irrigated   | N₂O               |
| Halvarson and Delgrosso 2013      | CO    | Corn             | Clay loam                      | NT, ST  | 7.6     | Irrigated   | N₂O               |
| Halvarson et al., 2010a           | CO    | Corn             | Clay loam                      | NT      | 7.6     | Irrigated   | N₂O               |
| Halvarson et al., 2010b           | CO    | Corn, barley, dry bean | Clay loam | NT      | 7.7–8.0 | Irrigated   | N₂O               |
| Helmets et al., 2012              | IA    | Corn             | Clay loam                      | CP      | 7.7     | Rainfed/Tile | NO₃               |
| Hernandez-Ramirez et al., 2009    | IN    | Corn             | Silty clay loam                | CP      | 6.6–7.6| Rainfed     | N₂O               |
| Hoben et al., 2011                | MI    | Corn             | Loam, Sandy loam               | CP      | 4.9–6.7 | Irrigated   | N₂O               |
| Hyatt et al., 2010                | MN    | Potato           | Loamy sand                     | CP      | ST      | Irrigated   | NH₃               |
| Janatalia et al., 2012            | CO    | Corn             | Clay loam                      | ST      | 7.8     | Irrigated   | NO₃               |
| Jaynes et al., 2013               | IA    | Corn             | Clay loam                      | CP      | Unk     | Rainfed/Tile | NO₃               |
| Jaynes et al., 2001               | IA    | Corn             | Clay loam                      | CP      | Unk     | Rainfed/Tile | NO₃               |
| Jemison and Fox 1994              | PA    | Corn             | Silt loam                      | CP      | Unk     | Unk         | NO₃               |
| Johnson et al., 2010              | MN    | Corn             | Loam                           | CP, ST  | 7.2     | Rainfed     | N₂O               |
| Kanwar et al., 1997               | IA    | Corn             | Silt                           | CP, MB, NT, Ridge | Unk     | Rainfed/Tile | NO₃               |
| Keller and Mengel 1986            | IN    | Corn             | Sandy loam, Silt loam          | NT      | 5.6     | Rainfed     | NH₃               |
| Kucharik and Brye 2003            | WI    | Corn             | Silt loam                      | CP, NT  | Unk     | Rainfed/Tile | NO₃               |
| Lawlor et al., 2008               | IA    | Corn             | Clay loam                      | CP      | 7.7     | Rainfed/Tile | NO₃               |
| Lawlor et al., 2011               | IA    | Corn             | Clay loam                      | CP      | 7.7     | Rainfed/Tile | NO₃               |
| LaHue et al., 2016                | CA    | Rice             | Clay                            | CP      | 5.3     | Irrigated   | N₂O               |
Table 1. Cont.

| Citation                  | State | Crop     | Texture          | Tillage | Soil pH | Water Mgmt | N Losses Monitored |
|---------------------------|-------|----------|------------------|---------|---------|------------|-------------------|
| Linquist et al., 2015     | AR    | Rice     | Silt loam        | CP      | Unk     | Irrigated  | N\textsubscript{2}O |
| Maharjan and Venterea 2013| MN    | Corn     | Silt loam        | CP      | Unk     | Rainfed    | N\textsubscript{2}O |
| Mitchell et al., 2013     | IA    | Loam     | Corn             | NT      | 6.4     | Rainfed    | N\textsubscript{2}O |
| Mosier et al., 2006       | CO    | Corn     | Clay loam        | CP, NT  | 7.7–7.8 | Irrigated  | N\textsubscript{2}O |
| Nash et al., 2012         | MO    | Corn     | Silt loam        | NT, ST  | 6.2     | Irrigated  | N\textsubscript{2}O |
| Omonode and Vyn 2013      | IA    | Corn     | Silt loam        | CP, NT  | Unk     | Rainfed    | N\textsubscript{2}O |
| Omonode and Vyn 2019      | IN    | Corn     | Silty clay loam  | NT, ST, MP, CP | Unk | Rainfed | N\textsubscript{2}O |
| Omonode et al., 2013      | IN    | Corn     | Silty clay loam  | CP, NT  | 6.1     | Rainfed/Tile | N\textsubscript{2}O |
| Nash et al., 2012         | MO    | Corn     | Silt loam, loam  | NT      | Unk     | Rainfed/Tile | N\textsubscript{2}O |
| Omonode et al., 2019      | CA    | Rice     | Clay             | CP      | 6.2     | Irrigated  | N\textsubscript{2}O |
| Prunty and Greenland 1997 | ND    | Potato, Corn | Loamy fine sand  | CP      | Unk     | Irrigated  | NO\textsubscript{3} |
| Randall and Vetsch 2005   | MN    | Corn     | Clay loam        | CP      | Unk     | Rainfed    | NO\textsubscript{3} |
| Randall et al., 2003      | MN    | Corn     | Clay loam        | CP      | Unk     | Rainfed    | NO\textsubscript{3} |
| Sexton et al., 1996       | MN    | Corn     | Sandy loam       | CP      | Unk     | Rainfed    | NO\textsubscript{3} |
| Steusloff et al., 2019    | MO    | Corn     | Silt loam        | CP      | 6.9, 5.6 | Rainfed    | N\textsubscript{2}O |
| Sistani et al., 2011      | KY    | Corn     | Silt loam        | NT      | 5.8     | Rainfed    | N\textsubscript{2}O |
| Smith et al., 1982        | LA    | Rice     | Silt loam        | CP      | 6.0     | Irrigated  | N\textsubscript{2}O |
| Sogbedji et al., 2000     | NY    | Corn     | Clay loam, Loamy sand | CP | Unk | Rainfed | NO\textsubscript{3} |
| Thapa and Chatterjee 2017 | MN    | Spring wheat | Silt loam        | CP      | 8.1     | Rainfed    | NH\textsubscript{3}, N\textsubscript{2}O |
| Thapa et al., 2015        | MN    | Spring wheat | Silt loam        | CP      | 8.4     | Rainfed    | NH\textsubscript{3}, N\textsubscript{2}O |
| Thornton and Valente 1996 | TN    | Corn     | Silt loam        | NT      | 5.75    | Rainfed    | N\textsubscript{2}O |
| Thornton et al., 1996     | TN    | Corn     | Silt loam        | NT      | 6.6     | Rainfed    | N\textsubscript{2}O |
| Toth and Fox 1998         | PA    | Corn     | Silt loam        | CP      | 6.2     | Irrigated  | NO\textsubscript{3} |
| Venterea et al., 2010     | MN    | Corn     | Silt loam        | CP      | 5.2–5.8 | Rainfed    | N\textsubscript{2}O |
| Vetsch et al., 2019       | MN    | Corn     | Clay loam        | CP      | Unk     | Rainfed/Tile | NO\textsubscript{3} |
| Walters and Malzer 1990   | MN    | Corn     | Sandy loam       | CP      | 5.7     | Irrigated  | NO\textsubscript{3} |
| Zhu and Fox 2003          | PA    | Corn     | Silt loam        | NT/CP   | 6.1     | Rainfed    | NO\textsubscript{3} |

Unk—Unknown; Tillage practice: CP—Chisel plow; ST—Strip tillage, NT—No-tillage; N losses: N\textsubscript{2}O—denitrification, NH\textsubscript{3}—volatilization, NO\textsubscript{3}—leaching. Main goal of this manuscript was to prepare the dataset of cumulative N losses. Peer-reviewed journal articles, reporting cumulative losses of denitrification, leaching, and volatilization during the growing season from non-leguminous crops in response to inorganic N fertilizer applications conducted in the conterminous United States. The dataset was studied and analyzed to determine the extent of N losses as influenced by (i) state, (ii) fertilizer-N management practices (source, application rate and time), (iii) main crop and previous crop in rotation, (iv) tillage practices, (v) water management (rainfed, irrigated and subsurface drainage), and (vi) soil properties (pH, texture, cation exchange capacity and SOM content). Correlation and regression of these factors with N losses were determined to understand the control of these factors.
2.2. Data Analysis

From sixty-two peer-reviewed journal articles, a total of 404, 26, and 358 observations of \( \text{CN}_2\text{O}, \text{CNO}_3^- \), and \( \text{CNH}_3 \) losses, respectively, were collected (Supplementary files). Exploratory data analyses, correlation and regression analyses were conducted using SAS Enterprise Guide 7.1 (SAS Institute, Cary, NC, USA) to determine the extent of N losses, and how they were influenced by fertilizer, soil, tillage, water, and crop management factors. For the normal distribution of data, numerical data were log-transformed and used for correlation and regression analyses. Pearson correlation coefficients between cumulative N losses and parameters like soil pH, clay content, CEC, water input, fertilizer N rate and crop yield were determined at 95% probability level. Simple and multiple linear regression relationships between N losses and N rate were conducted using Proc Reg procedure using SAS Enterprise Guide 7.1. The best model for the multiple linear regression was selected using the maximum adjusted \( R^2 \) value and Akaike Information Criterion score.

3. Results

First, extent of cumulative \( \text{N}_2\text{O}, \text{NH}_3, \) and \( \text{NO}_3 \) losses across the conterminous United States is presented, followed by control of these losses by nitrogenous fertilizer management practices (application rate, time, and placement), crop species, water management and soil properties are discussed.

3.1. Extent of Cumulative N Losses

Within 62 studies, values of \( \text{CN}_2\text{O} \) \((n = 404)\), \( \text{CNO}_3^- \) \((n = 358)\), and \( \text{CNH}_3 \) \((n = 26)\) were ranged between −0.04 to 16.9 kg N ha\(^{-1}\), 0 to 257 kg N ha\(^{-1}\), and 2.50 to 50.9 kg N ha\(^{-1}\), with average values of 2.12 kg N ha\(^{-1}\), 37.7 kg N ha\(^{-1}\), and 11.5 kg N ha\(^{-1}\), respectively (Figure 1). Global estimates of \( \text{N}_2\text{O} \) fluxes ranged between 0 and 30 kg N ha\(^{-1}\) yr\(^{-1}\) [37]. Previous estimates of \( \text{NO}_3^- \) leaching loss ranged between 4 and 155 kg N ha\(^{-1}\) yr\(^{-1}\) (Cameron et al., 2013). According to Pan et al. (2016), the amount of \( \text{NH}_3\)-N volatilized per cropping season was highest in South Asia (37.5 kg N ha\(^{-1}\)), followed by North America (22.2 kg N ha\(^{-1}\)) and East Asia (20.6 kg N ha\(^{-1}\)).

![Figure 1](image-url)  
Figure 1. Extent of cumulative nitrogen losses (kg N ha\(^{-1}\)) during growing season from non-leguminous field crops, generated from data published in peer-reviewed manuscripts.
Reported cumulative N losses for different states were presented in Table 2. For CN$_2$O, maximum number of observations (n = 100, 25%) was found within the Colorado state. The highest average value of CN$_2$O (6.62 kg N ha$^{-1}$) was observed from the Tennessee state; however, only six observations were reported. The lowest average value of CN$_2$O was observed from Louisiana, whereas the highest maximum value was detected in the Illinois state. The spatial distribution of N$_2$O sources closely mirrors data on fertilizer application with particularly large N$_2$O sources over the US Cornbelt [38].

The maximum number of CNO$_3^-$ values were reported from Iowa. Both the highest average value and the highest maximum value of CNO$_3^-$ was noted in Minnesota. The major areas exhibiting high NO$_3^-$ concentration in ground water were areas of intensive row cropping and heavy fertilization, locally intensive animal feeding and handling operations, and areas of irrigation and fertilization of vegetable crops on sandy soils [39]. An assessment of groundwater NO$_3^-$ concentration in in the United States indicated that the highest concentrations were observed in parts of the Northeast, the Central Plains, and the Southwest [40].

The number of CNH$_3$ observations was extremely low; the highest average value and the maximum values of CNH$_3$ were reported for the Indiana soils. Ammonia emissions from fertilizer application are dependent on regional crop schedules. According to an estimate, the highest emissions were found in Kansas (13,100 Mg), Iowa (17,000 Mg), California (8800 Mg) and Ohio (11,100 Mg) in March, April, May, and June, respectively, across the conterminous United States [41].

Table 2. Extent of variations in cumulative nitrogen losses (kg N ha$^{-1}$) during growing season across different states of the conterminous United States

| State          | n  | Mean | Minimum | Maximum |
|----------------|----|------|---------|---------|
| **Denitrification loss (kg N$_2$O-N ha$^{-1}$)** |    |      |         |         |
| Arkansas       | 16 | 0.22 | −0.01   | 1.05    |
| California     | 26 | 0.40 | −0.04   | 1.54    |
| Colorado       | 100| 0.81 | 0.11    | 3.56    |
| Iowa           | 21 | 5.60 | 0.32    | 16.3    |
| Illinois       | 27 | 4.28 | 0.72    | 16.9    |
| Indiana        | 18 | 2.88 | 0.79    | 6.88    |
| Kentucky       | 14 | 2.88 | 1.01    | 5.97    |
| Louisiana      | 5  | 0.11 | 0.07    | 0.17    |
| Minnesota      | 66 | 2.93 | 0.25    | 11.2    |
| Missouri       | 16 | 4.57 | 1.12    | 7.70    |
| Nebraska       | 10 | 2.72 | 1.25    | 4.91    |
| New York       | 3  | 3.03 | 1.90    | 4.90    |
| Pennsylvania   | 28 | 0.72 | 0.10    | 2.85    |
| Tennessee      | 6  | 6.62 | 1.43    | 13.8    |

| **Leaching loss (kg NO$_3^-$-N ha$^{-1}$)** |    |      |         |         |
| Connecticut    | 6  | 27.8 | 4.00    | 61.0    |
| Iowa           | 176| 34.1 | 0       | 109     |
| Michigan       | 12 | 34.7 | 11.0    | 89.0    |
| Minnesota      | 109| 45.4 | 4.00    | 257     |
| North Dakota   | 8  | 42.3 | 3.00    | 118     |
| New York       | 12 | 14.4 | 5.90    | 34.9    |
| Pennsylvania   | 23 | 43.0 | 4.50    | 135     |
| Wisconsin      | 12 | 39.1 | 3.20    | 102     |

| **Volatilization loss (kg NH$_3$-N ha$^{-1}$)** |    |      |         |         |
| Colorado       | 2  | 6.20 | 5.20    | 7.20    |
| Indiana        | 4  | 21.4 | 9.20    | 50.9    |
| Minnesota      | 14 | 5.70 | 2.50    | 11.1    |
| Montana        | 6  | 20.2 | 10.0    | 34.4    |
3.2. Control of Fertilizer N Management

Fertilizer N application rate had significant influence on CN\textsubscript{2}O and CNO\textsubscript{3}\textsuperscript{−} (Table 3). Fertilizer N application rate can explain 38% and 27% of the variability in CN\textsubscript{2}O and CNO\textsubscript{3}\textsuperscript{−}, respectively. Fertilizer N rate had a positive effect on both area- and yield-scaled N\textsubscript{2}O and NO\textsubscript{3}\textsuperscript{−} losses [2]. A 30% increase in fertilizer-N rate increased annual NO\textsubscript{3}\textsuperscript{−} leaching by 56%, while corn yield increased by only 1% [42]. In Iowa, to achieve an average NO\textsubscript{3}\textsuperscript{−} concentration less than 10 mg L\textsuperscript{−}1 in subsurface drainage, the N application rate for corn would need to be less than 112 kg N ha\textsuperscript{−}1 [29]. Within the corn production system, linear regression indicates that each unit rise in fertilizer N application rate results in an N\textsubscript{2}O-N loss of 0.01 kg N\textsubscript{2}O-N ha\textsuperscript{−}1 and leaching loss of 0.12 kg NO\textsubscript{3}−N ha\textsuperscript{−}1 (Figure 2).

| Variables               | Denitrification | Leaching | Volatilization |
|-------------------------|-----------------|----------|----------------|
| N rate (kg N ha\textsuperscript{−}1) | r = 0.38 | Pr > | 0.27 | 0.09 |
|                         | n = 399       |          | 356            | 26   |
| Crop yield (Mg ha\textsuperscript{−}1) | r = −0.015 | Pr > | 0.12 | 0.66 |
|                         | n = 305       |          | 349            | 14   |
| Water input (mm)        | r = 0.31      | Pr > | 0.29 | −0.39 |
|                         | n = 348       |          | 308            | 20   |
| SOM (g kg\textsuperscript{−}1)  | r = 0.44      | Pr > | −0.08 | −0.61 |
|                         | n = 340       |          | 251            | 24   |
| Clay (g kg\textsuperscript{−}1) | r = −0.42 | Pr > | 0.06 | 0.55 |
|                         | n = 233       |          | 71             | 16   |
| pH                     | r = −0.21     | Pr > | −0.07 | −0.65 |
|                         | n = 337       |          | 163            | 26   |
| CEC (Cmole+ kg\textsuperscript{−}1) | r = −0.23 | Pr > | 0.03 | −0.72 |
|                         | n = 135       |          | 41             | 24   |

Table 3. Pearson correlation coefficient (r) and significance level at 95% significance level among soil pH, clay content, cation exchange capacity, water input (rainfall and irrigation), fertilizer N application rate, and crop yield and N losses. Data were log-transformed for the normal distribution of the data.

Influences of fertilizer-N source on N losses are presented in Table 4. Most of the CN\textsubscript{2}O and CNH\textsubscript{3} observations were made on urea application, and urea ammonium nitrate (UAN) was the most popular for the CNO\textsubscript{3}− observations. The highest average CN\textsubscript{2}O and CNO\textsubscript{3}− values were observed with ammonium nitrate (AN) application. The application of anhydrous NH\textsubscript{3} had the highest maximum CN\textsubscript{2}O. The application of anhydrous NH\textsubscript{3} lost 12.3 kg CN\textsubscript{2}O ha\textsuperscript{−}1 or 7.33% of applied N, almost double of urea application (6.34 kg CN\textsubscript{2}O ha\textsuperscript{−}1 or 3.77% of applied N) [43]. Applications of nitrification or both urease and nitrification inhibitors reduced CN\textsubscript{2}O values, but the ESN was not effective in reducing CN\textsubscript{2}O. The application of ESN delayed the N\textsubscript{2}O flux peak by 3 to 4 wk compared with other N sources, but CN\textsubscript{2}O did not differ significantly [44]. ESN was not effective in reducing N\textsubscript{2}O emission.
under rainfed condition [22]. The N fertilizer source and climatic conditions need consideration when selecting N sources to reduce denitrification loss [44].

The application of AN had the highest maximum CNO$_3^-$, followed by urea (Table 4). The contribution of N source to NO$_3^-$ leaching was calcium nitrate [Ca(NO$_3$)$_2$] > ammonium sulfate [(NH$_4$)$_2$SO$_4$] > check ≥ urea [CO(NH$_2$)$_2$] [45]. The minimum and maximum values of CNO$_3^-$ for urea with and without nitrapyrin addition were almost similar. Nitrification inhibitor additions had varying success depending on the influences of climate and soil type on the microbial process of nitrification [46]. This dataset indicates that urea application had the highest average and maximum values of CNH$_3$ (Table 4). The greatest risk of NH$_3$ volatilization losses occur from urea and ammonium hydroxide fertilizers [34].

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Linear regression relationship between fertilizer N application rate (kg N ha$^{-1}$) and (a) cumulative nitrous oxide flux (kg N$_2$O-N ha$^{-1}$) and (b) leaching loss of nitrate (kg NO$_3$-N ha$^{-1}$) within corn production system.

The application of both urease and/or nitrification inhibitors had potential to reduce the CNH$_3$ loss compared to urea alone. A urease inhibitor like NBPT addition can reduce NH$_3$ loss by 52% [36]. The application of both urease and nitrification inhibitor reduced CNH$_3$ by 34% under spring wheat production system in Minnesota [47].
Table 4. Nitrogen losses as influenced by fertilizer-N sources and enhanced efficiency N fertilizers (addition of additives and slow release N fertilizers).

| Fertilizer Source       | n  | Mean   | Minimum | Maximum |
|-------------------------|----|--------|---------|---------|
| Denitrification loss (kg N₂O ha⁻¹) |
| AA                      | 37 | 3.82   | 0.07    | 16.9    |
| AN                      | 9  | 5.51   | 2.03    | 8.54    |
| UAN                     | 42 | 2.38   | 0.10    | 16.3    |
| Urea                    | 134| 1.72   | -0.04   | 14.1    |
| ESN                     | 32 | 2.19   | 0.22    | 9.77    |
| SuperU                  | 25 | 1.19   | 0.24    | 3.06    |
| UAN + Agrotain          | 8  | 1.07   | 0.16    | 3.90    |
| UAN + Nitrapyrin        | 8  | 1.89   | 0.32    | 5.37    |
| Urea + Nitrapyrin       | 6  | 2.16   | 0.36    | 5.71    |

Leaching loss (kg NO₃⁻-N ha⁻¹)

|                | n  | Mean   | Minimum | Maximum |
|----------------|----|--------|---------|---------|
| AA             | 55 | 38.8   | 4.48    | 122     |
| AN             | 40 | 64.6   | 4.00    | 257     |
| Aqueous ammonia| 26 | 45.8   | 2.00    | 86.0    |
| Urea           | 30 | 51.8   | 16.0    | 141     |
| UAN            | 111| 28.6   | 0       | 109     |
| AA + Nitrapyrin| 28 | 29.0   | 4.00    | 80.0    |
| Urea + Nitrapyrin| 12 | 48.9   | 18.0    | 139     |

Volatilization loss (kg NH₃-N ha⁻¹)

|                | n  | Mean   | Minimum | Maximum |
|----------------|----|--------|---------|---------|
| Urea           | 13 | 16.6   | 4.41    | 50.9    |
| UAN            | 3  | 10.3   | 7.20    | 14.6    |
| Urea + Nitrapyrin| 4  | 7.03   | 4.08    | 11.1    |
| SuperU         | 4  | 4.68   | 4.08    | 5.82    |

AA: Anhydrous NH₃; AN: Ammonium nitrate; UAN: Urea Ammonium nitrate.

The impacts of fertilizer placement on three N losses are presented in Table 5. The injection of fertilizer-N had the highest average and maximum CN₂O values. The most common application methods, broadcast and incorporation, and banding, have similar average and maximum CN₂O losses. Broadcast fertilizer, in comparison to injecting or banding, reduced overall N₂O emissions by 25–33%. The banding of fertilizer-N had the highest average and maximum amount of CNO₃⁻ values, followed by broadcast and broadcast and incorporation, and then injection [2]. Deep-banded urea had significantly higher soil NO₃⁻-N concentrations in deep soil layers compared to the deep banding of urea with nitrapyrin additions on a poorly drained claypan soil [48]. An opposite trend, broadcast-incorporated application, had a higher nitrate immobilization in the top 90 cm than with the banded applications, in coarse silt loam soils [49]. The broadcast of fertilizer-N had the highest average and maximum CNH₃ values. The placement of N fertilizers at 3–5 cm below the soil surface reduces the risk of NH₃ volatilization because it reduces the NH₃/NH₄⁺ concentration at the soil surface [34].

The effects of fertilizer application time on N losses are presented in Table 6. For denitrification loss, most of the studies were conducted in the spring. The average values were similar for spring and split between fall and spring; however, one-time pre-plant spring application had a higher maximum value than split application. The late fall application of anhydrous NH₃ before freeze-up increased N₂O emissions at thaw and decreased emissions for the early growing season compared to spring pre-plant application [50]. The split application of fertilizer-N during spring increased CNO₃⁻ losses compared to a single application during either fall or spring. The portion of the midseason N application not taken up by corn was available for leaching for field with subsurface drainage [51]. The single pre-plant application of fertilizer-N had increased CNH₃ value split between fall and spring. When fertilizer applied in summer, with high soil temperature and low soil moisture contents, NH₃ volatilization tended to increase [1]. On the contrary, the researcher found that CNH₃ loss from surface urea application was greater for late fall (16.4%) and winter (11.4%) than for spring (2.0%) applications [2].
Table 5. Effect of fertilizer placement on nitrogen losses (kg N ha\(^{-1}\)).

| Fertilizer Placement Method                             | n  | Mean  | Minimum | Maximum |
|--------------------------------------------------------|----|-------|---------|---------|
| Denitrification loss (kg N\(_2\)O-N ha\(^{-1}\))       |    |       |         |         |
| Broadcast                                              | 52 | 2.39  | 0.07    | 7.70    |
| Broadcast-incorporated                                 | 105| 1.84  | -0.04   | 14.1    |
| Banded                                                | 120| 1.44  | 0.10    | 12.5    |
| Injected                                              | 43 | 4.81  | 0.07    | 16.9    |
| Broadcast, banded                                      | 14 | 2.01  | 0.32    | 6.12    |
| Broadcast-incorporated, sidedress                      | 10 | 2.72  | 1.25    | 4.91    |
| Sidedress                                             | 6  | 2.88  | 2.38    | 3.36    |
| Deep banded                                           | 4  | 4.42  | 3.82    | 5.71    |
| Drilled                                               | 2  | 0.14  | 0.11    | 0.17    |
| Midrow banded                                         | 6  | 3.25  | 0.84    | 6.07    |
| Subsurface banded                                     | 2  | 1.36  | 1.35    | 1.37    |
| Topdress                                              | 2  | 0.10  | 0.09    | 0.11    |
| Leaching loss (kg NO\(_3\)-N ha\(^{-1}\))             |    |       |         |         |
| Broadcast                                              | 39 | 46.8  | 5.90    | 141     |
| Broadcast-incorporated                                 | 24 | 54.4  | 16.0    | 141     |
| Broadcast-incorporated, sidedress                      | 6  | 38.0  | 27.0    | 59.0    |
| Banded                                                | 14 | 81.3  | 5.90    | 257     |
| Injected                                              | 127| 33.6  | 0.40    | 122     |
| Sidedress                                             | 78 | 34.0  | 3.00    | 118     |
| Volatilization loss (kg NH\(_3\)-N ha\(^{-1}\))       |    |       |         |         |
| Broadcast                                              | 10 | 20.7  | 9.20    | 50.9    |
| Broadcast-incorporated                                 | 13 | 5.95  | 3.48    | 11.1    |
| Banded                                                | 2  | 6.20  | 5.20    | 7.20    |

Table 6. Nitrogen losses (kg N ha\(^{-1}\)) as influence by fertilizer application time.

| Application Time                          | n  | Mean  | Minimum | Maximum |
|-------------------------------------------|----|-------|---------|---------|
| Denitrification loss (kg N\(_2\)O-N ha\(^{-1}\)) |    |       |         |         |
| Split between fall and spring             | 10 | 2.72  | 1.25    | 4.91    |
| Spring                                    | 384| 2.14  | -0.04   | 16.9    |
| Leaching loss (kg NO\(_3\)-N ha\(^{-1}\))  |    |       |         |         |
| Fall                                      | 44 | 36.1  | 6.00    | 122     |
| Spring                                    | 246| 34.9  | 0.0     | 141     |
| Split during spring                       | 38 | 67.2  | 3.00    | 257     |
| Volatilization loss (kg NH\(_3\)-N ha\(^{-1}\)) |    |       |         |         |
| Spring                                    | 19 | 9.22  | 3.48    | 50.9    |
| Split between fall and spring             | 6  | 20.0  | 10.0    | 34.4    |

3.3. Control of Crop Species

The influences of crop species on N losses are presented in Table 7. Denitrification losses were mostly measured for corn production, particularly for continuous corn, followed by corn–soybean rotation. Corn production had the highest average CN\(_2\)O loss of 2.52 Kg N\(_2\)O-N ha\(^{-1}\), followed by potato (1.02 Kg N\(_2\)O-N ha\(^{-1}\)) and spring wheat (0.98 Kg N\(_2\)O-N ha\(^{-1}\)). The rice production system had the least average CN\(_2\)O, and it showed a negative minimum value. Due to inundation in wetland rice, N\(_2\)O is consumed before being released into the atmosphere.\(^\text{18}\) Potato with winter rye in rotation had the highest average and maximum CNO\(_3\) loss. Continuous corn had the maximum CNO\(_3\) loss, followed by the corn–soybean rotation. Continuous corn also had the highest average and maximum CNH\(_3\) loss. Crop yield is significantly related to leaching and volatilization losses, but not with denitrification loss (Table 3).
Table 7. Nitrogen losses (kg N ha\(^{-1}\)) as influenced by previous crop.

| Main Crop | Previous Crop | n  | Mean  | Minimum | Maximum |
|-----------|---------------|----|-------|---------|---------|
| Denitrification loss (kg N\(_2\)O-N ha\(^{-1}\)) |
| Corn      | Alfalfa       | 6  | 5.27  | 4.21    | 6.44    |
| Barley    | 4             | 0.52| 0.19  | 0.83    |
| Corn      | 166           | 1.92| 0.10  | 16.9    |
| Cereal rye| 8             | 9.23| 4.50  | 11.2    |
| Dry bean  | 4             | 0.74| 0.14  | 1.66    |
| Soybean   | 120           | 2.89| 0.23  | 16.3    |
| Total     | 323           | 2.52| 0.10  | 16.9    |
| Potato    | Cereal rye    | 11 | 1.02  | 0.42    | 2.11    |
| Barley    | Corn          | 5  | 0.45  | 0.15    | 0.81    |
| Spring wheat | Soybean      | 14 | 0.98  | 0.25    | 2.40    |
| Rice      | 34            | 0.34| -0.04 | 1.54    |
| Soybean   | 8             | 0.30| 0.03  | 1.05    |
| Leaching loss (kg NO\(_3\)-N ha\(^{-1}\)) |
| Corn      | Alfalfa       | 12 | 14.4  | 5.90    | 34.9    |
| Corn      | 106           | 41.1| 3.20  | 141     |
| Corn/Lupine | 16           | 51.8| 15.0  | 141     |
| Potato    | 4             | 47.3| 3.00  | 118     |
| Soybean   | 206           | 32.5| 0.0   | 135     |
| Potato    | Corn          | 4  | 37.3  | 8.00    | 61      |
| Winter Rye| 10            | 112 | 18.0  | 257     |
| Volatilization loss (kg NH\(_3\)-N ha\(^{-1}\)) |
| Corn      | 6             | 16.32| 5.25| 50.9    |
| Spring wheat | 14          | 0.98| 0.25  | 2.40    |
| Winter wheat | Fallow      | 6  | 20.2  | 10.0    | 34.4    |

Influence of Tillage

Controls of tillage practices on N losses are presented in Figure 3. Chisel plow had a slightly higher average (2.13 kg N\(_2\)O-N ha\(^{-1}\)) and maximum (16.9 kg N\(_2\)O-N ha\(^{-1}\)) CN\(_2\)O than under no-tillage (1.91 and 16.3 kg N\(_2\)O-N ha\(^{-1}\), respectively). One study [20] concluded no clear positive or negative effect of tillage on denitrification. However, in Indiana, reduced N\(_2\)O emissions were observed in the order of moldboard plow > chisel plow > strip till > no-till for continuous corn production [24]. For CNO\(_3\)\(^-\), Chisel plow had higher average (37.8 kg N ha\(^{-1}\)) and maximum (257 kg N ha\(^{-1}\)) values than no-tillage (29.9 and 108 kg N ha\(^{-1}\), respectively). Soil disturbances were associated with tillage increases aeration and incorporate crop residues; a flush of mineralization and nitrification often occurs under such conditions, resulting in the loss of accumulation of leachable NO\(_3\)\(^-\)-N in the soil [52]. On the contrary, no-tillage had higher average (20.7 kg N ha\(^{-1}\)) and maximum (50.9 kg N ha\(^{-1}\)) CNH\(_3\) values than chisel plow (5.70 and 11.1 kg N ha\(^{-1}\), respectively). Urease activity in the top 1 cm was significantly enhanced, being, on average, 4.2 times higher in NT than in CP soils; moreover, residues reduced the adsorption of NH\(_4\)\(^+\) on soil particles [53].
3.4. Control of Water Management

The influences of water management practices (rainfed, irrigation, and subsurface drainage) on N losses are presented in Table 8. The mean value of CN\textsubscript{2}O was the highest from fields under subsurface drained conditions, and the average value of CN\textsubscript{2}O was lower under irrigated condition than soils under rainfed and subsurface drained conditions. Denitrification is strongly affected by water-filled porespace, and combined N\textsubscript{2}O and N\textsubscript{2} losses were greater in wetter soils [20]. For leaching loss, the average and maximum values of CNO\textsubscript{3}\textsuperscript{−} were higher for irrigated soils than rainfed and subsurface drained conditions. Excessive rates of irrigation can cause leaching, particularly under flood irrigation [34]. Adjusting irrigation to crops’ demand reduced leaching by 80% without a reduction in yield [54]. Rainfed soils had comparatively higher value of CN\textsubscript{H} than irrigated soils. Another study observed the greatest amount of NH\textsubscript{3} loss (60% of applied N) occurred when no irrigation was applied, and NH\textsubscript{3} losses can be reduced to 2.8% of applied N by applying irrigation immediately after urea [55]. The amount of water input (sum of rainfall during growing season and irrigation) had significant positive relationships with CN\textsubscript{2}O and CNO\textsubscript{3}\textsuperscript{−} losses (Table 3).

Table 8. Effect of water management practices on N losses (kg N ha\textsuperscript{−1}).

| Water Mgmt.                  | n  | Mean   | Minimum | Maximum |
|------------------------------|----|--------|---------|---------|
| Denitrification loss (kg N\textsubscript{2}O-N ha\textsuperscript{−1}) |
| Irrigated                    | 170| 1.35   | −0.04   | 11.2    |
| Rainfed                      | 197| 2.27   | −0.01   | 16.3    |
| Subsurface drained           | 34 | 5.06   | 0.79    | 16.9    |
| Leaching loss (kg NO\textsubscript{3}N ha\textsuperscript{−1}) |
| Irrigated                    | 69 | 56.0   | 3.00    | 257     |
| Rainfed                      | 58 | 30.1   | 4.00    | 135     |
| Subsurface drained           | 222| 34.2   | 0.0     | 109     |
| Volatilization loss (kg NH\textsubscript{3}N ha\textsuperscript{−1}) |
| Irrigated                    | 2  | 6.20   | 5.20    | 7.20    |
| Rainfed                      | 20 | 10.1   | 2.50    | 34.4    |
3.5. Control of Soil Properties

The influences of soil textural class on N losses are presented in Table 9. Most of the CN$_2$O observations were made on silt loam soils, followed by clay loam soils; clay loam soils were mostly studied for CNO$_3^-$ and CNH$_3$ losses. A study site, located in Illinois and dominated by two groups, silt clay loam, and loam, had the highest average CN$_2$O loss, whereas the highest maximum loss was observed under a site dominated by silt loam and silty clay loam (located in central Iowa). More capillary pores within aggregates in fine textured soils have a slow percolation rate and can more easily reach and maintain anaerobic conditions than in coarse-textured soils [18].

Table 9. Influence of soil textural class on cumulative N losses based on observations collected across conterminous United States.

| Texture            | n  | Mean  | Minimum | Maximum |
|--------------------|----|-------|---------|---------|
|                    |    | Denitrification loss (kg N$_2$O-N ha$^{-1}$) |         |         |
| Clay               | 21 | 0.39  | −0.04   | 1.54    |
| Clay loam          | 105| 0.80  | 0.11    | 3.56    |
| Loam               | 54 | 2.31  | 0.34    | 6.99    |
| Loamy sand         | 19 | 4.47  | 0.42    | 11.2    |
| Sandy loam         | 6  | 1.11  | 0.52    | 1.94    |
| Silt loam          | 137| 2.25  | −0.01   | 16.3    |
| Silty clay loam    | 40 | 2.59  | 0.66    | 6.88    |
| Silt loam + Silty clay loam | 12 | 5.20 | 0.97  | 16.9    |
| Silty clay loam + loam | 10 | 7.51 | 2.30  | 12.5    |

|                    |    | Leaching loss (kg NO$_3^-$-N ha$^{-1}$) |         |         |
|--------------------|----|--------------------------------------|---------|---------|
| Clay loam          | 175| 35.7                                 | 0.00    | 122     |
| Loam               | 51 | 19.4                                 | 0.40    | 89.0    |
| Loamy sand         | 24 | 65.4                                 | 3.00    | 257     |
| Sandy loam         | 49 | 45.2                                 | 4.00    | 141     |
| Silt               | 24 | 42.4                                 | 4.48    | 108     |
| Silt loam          | 35 | 41.7                                 | 3.20    | 135     |

|                    |    | Volatilization loss (kg NH$_3$-N ha$^{-1}$) |         |         |
|--------------------|----|---------------------------------------------|---------|---------|
| Clay loam          | 8  | 16.7                                       | 5.20    | 34.4    |
| Sandy loam         | 2  | 32.6                                       | 14.6    | 50.9    |
| Silt loam          | 9  | 5.64                                       | 2.50    | 10.8    |
| Silty clay loam    | 7  | 7.00                                       | 3.48    | 11.1    |

Loamy sand soils had the highest average and maximum CNO$_3^-$ loss, whereas the least values for average and maximum CNO$_3^-$ were found under loam. The study supported the theory that NO$_3^-$ losses were consistently higher on the loamy sand than on the clay loam soils [56]. Clay loam soils had the highest average and maximum CNH$_3$ loss, and silt loam soils had the least.

The relationships of soil properties, SOM, clay content, pH, and CEC with N losses are presented in Table 3. Denitrification was positively associated with SOM content, whereas volatilization loss had a negative association with SOM. An opposite trend was observed in the case of clay content; this was negatively related to denitrification and positively related to volatilization losses (Table 3).

Multiple linear regression equation for the N$_2$O loss is $-0.173 \times (\text{CEC}) + 0.013 \times (\text{clay content}) + 0.008 \times (\text{fertilizer-N rate})$ with adjusted $R^2$ value of 0.42 and model $p < 0.001$. Multiple regression equation for the NO$_3^-$ leaching loss is $-0.723 \times (\text{clay content}) + 0.331 \times (\text{fertilizer-N rate}) + 0.273 \times (\text{water input})$ with adjusted $R^2$ value of 0.57 and model $p < 0.001$.

4. Limitations and Future Research Needs

Among the three N losses studied, volatilization loss had only 26 observations. Most of the volatilization losses occur soon after fertilizer application, hence some studies had recorded for a limited
time. For example, one reported volatilization loss only for 120 h after application [57], and another research studied cumulative volatilization loss for 24 days after application [55]. A significant amount of N is lost through volatilization from agricultural systems [1]; comprehensive volatilization loss studies are required to determine the extent of loss and their controlling factors across different production systems.

For the other two losses, denitrification and leaching, most of the studies are restricted to within Colorado and Iowa, respectively. Several states with a significant area under agricultural production like Ohio, Florida, Kansas, Mississippi, had hardly any information on N losses. Moreover, most of the studies were conducted on a corn-based production system. Studies on shallow rooted crops with a significant N demand like potato were extremely meagre (Table 7). There are not many N loss studies on cotton, sunflower, canola and sugarbeets.

The main goal was to publish the research data to facilitate future research studies. Some authors reported cumulative N loss data from multiple treatments in figures; the extraction of N loss numbers from these figures is tedious, particularly for calculating CN\(_2\)O from daily N\(_2\)O flux. Providing the raw data in an appendix will greatly facilitate the further use of these data. Several studies did not provide basic experimental conditions and site information. It is critical to provide ancillary data related to climate variables (rainfall and temperature), crop yield and soil properties (bulk density, texture, SOM, pH, and CEC) to explain the control of N losses across agricultural systems.

This manuscript provides the current understanding, knowledge gap and future research needs of denitrification, leaching and volatilization. Most of the research studies were concentrated on corn production systems of the Great Plains. Finalizing the 4R (right rate, right source, right time, and right placement), fertilizer-N strategies should be based on local climate and crop and soil management practices. Crop rotation and water management decisions have significant influences on denitrification and leaching. Soil properties like clay content and SOM could explain the spatiotemporal variation in denitrification and leaching losses across the conterminous United States. Targeted research studies from states/regions lacking N loss data would facilitate the predictive modeling framework and policy development.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/2504-3129/1/1/5/s1, Excel file of nitrogen loss data with ancillary information of studies used in this review, Word file: List of references for journal articles reporting nitrogen loss measurements from non-legume agricultural production system used in this review.

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