Nitrogen

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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 (CN_2O), ammonia volatilization (CNH_3), and nitrate leaching (CNO_3^-) 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 CN_2O, CNH_3, and CNO_3^- 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 CN_2O, CNH_3 and CNO_3^-, respectively. Most CN_2O and CNO_3^- observations were reported from Colorado (*n* = 100) and Iowa (*n* = 176), respectively. The highest values of CN_2O, and CNO_3^- were reported from Illinois and Minnesota states, and corn and potato (*Solanum tuberosum*), respectively. The application of anhydrous NH_3 had the highest value of CN_2O loss, and ammonium nitrate had the highest CNO_3^- loss. Among the different placement methods, the injection of fertilizer-N had the highest CN_2O loss, whereas the banding of fertilizer-N had the highest CNO_3^- loss. The maximum CNO_3^- loss was higher for chisel than no-tillage practice. Both CN_2O and CNO_3^- 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 (NO_3^-) leaching and gases like ammonia (NH_3) and nitrous oxide (N_2O) 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 N_2O emissions and NO_3^- leaching losses that conform and potentially exceeds 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 N_2O 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 N_2O 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 N_2O emission from cultivated soils were 1.0 kg N_2O-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 N_2O emission. A recent meta-analyses study had concluded an equivalent N_2O 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 N_2O 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 N_2O 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 N_2O 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, N_2O emission [23]. Fertilizer N management practices interact with other crop, soil and water management decisions. Tillage affected N_2O 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 N_2O 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 NO_3 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 NO_3 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 NO_3 were lost in corn phase and 46% during soybean [32]. Fertilizer application timing and inhibitor addition can influence NO_3 concentration [27]. Researchers found that NO_3 concentration and loss followed the order: fall N > split N > spring N = fall N + nitrapyrin [33].

Nitrogen from fertilizers containing ammonia-based form, urea [$CO(NH_2)_2$], and ammonium sulfate [$(NH_4)_2SO_4$] 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 NH_3 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 NH_3 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 (CN_2O, CNO_3^-, and CNH_3) 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
1	Adviento-Borbe et al., 2007	NE	Corn	Silty clay loam	CP	6.14	Irrigated	N_2O
2	Adviento-Borbe et al., 2013	CA, AR	Rice	Clay loam, Clay, Silt loam	CP	5.46–6.19	Irrigated	N_2O
3	Bakhsh et al., 2002	IA	Corn	Loam	CP, NT	Unk	Rainfed/Tile	NO_3
4	Bakhsh et al., 2007	IA	Corn	Loam	CP	Unk	Rainfed/Tile	NO_3
5	Bakhsh et al., 2010	IA	Corn	Loam	CP	Unk	Rainfed/Tile	NO_3
6	Basso and Ritchie 2005	MI	Corn	Loam	CP	5.5	Rainfed/Tile	NO_3
7	Bronson et al., 1992	CO	Corn	Clay loam	CP	7.2	Irrigated	N_2O
8	Curtis et al., 2014	PA	Corn	Silt loam	NT	Unk	Rainfed	NO_3
9	Duxbury and McConnaughey 1986	NY	Corn	Silt loam	Unk	6.9	Unk	N_2O
10	Engel et al., 2017	MT	Winter wheat	Clay loam	NT	6.3, 7.3	Rainfed	NH_3
11	Errebhi et al., 1998	MN	Potato	Loamy sand	CP	6.7	Irrigated	NO_3
12	Fernandez et al., 2015	IL	Corn	Silt loam, Silty clay loam	CP	6.2	Rainfed/Tile	N_2O
13	Fujinuma et al., 2011	MN	Corn	Loamy sand	CP	4.85	Irrigated	N_2O
14	Graham et al., 2018	IL	Corn	Silt loam Silty clay loam	CP	6.3, 6.1	Rainfed	N_2O
15	Guillard et al., 1999	CT	Corn	Sandy loam	CP	Unk	Rainfed/Tile	NO_3
16	Halvarson et al., 2008	CO	Corn, barley, dry bean	Clay loam	CP, NT	7.7–7.8	Irrigated	N_2O
17	Halvarson and Delgrosso 2012	CO	Corn	Clay loam	NT	7.6	Irrigated	N_2O
18	Halvarson and Delgrosso 2013	CO	Corn	Clay loam	NT, ST	7.6	Irrigated	N_2O
19	Halvarson et al., 2010a	CO	Corn	Clay loam	NT	7.6	Irrigated	N_2O
20	Halvarson et al., 2010b	CO	Corn, barley, dry bean	Clay loam	NT	7.7–8.0	Irrigated	N_2O
21	Helmers et al., 2012	IA	Corn	Clay loam	CP	7.7	Rainfed/Tile	NO_3
22	Hernandez-Ramirez et al., 2009	IN	Corn	Silty clay loam	CP	Unk	Rainfed/Tile	N_2O
23	Hoben et al., 2011	MI	Corn	Loam, Sandy loam	CP	6.6–7.6	Rainfed	N_2O
24	Hyatt et al., 2010	MN	Potato	Loamy sand	CP	4.9–6.7	Irrigated	N_2O
25	Janatalia et al., 2012	CO	Corn	Clay loam	ST	7.8	Irrigated	NH_3
26	Jaynes et al., 2013	IA	Corn	Clay loam	CP	Unk	Rainfed/Tile	NO_3
27	Jaynes et al., 2001	IA	Corn	Clay loam	CP	Unk	Rainfed/Tile	NO_3
28	Jemison and Fox 1994	PA	Corn	Silt loam	CP	Unk	Unk	NO_3
29	Johnson et al., 2010	MN	Corn	Loam	CP, ST	7.2	Rainfed	N_2O
30	Kanwar et al., 1997	IA	Corn	Silt	CP, MB, NT, Ridge	Unk	Rainfed/Tile	NO_3
31	Keller and Mengel 1986	IN	Corn	Sandy loam, Silt loam	NT	5.6	Unk	NH_3
32	Kucharik and Brye 2003	WI	Corn	Silt loam	CP, NT	Unk	Rainfed/Tile	NO_3
33	Lawlor et al., 2008	IA	Corn	Clay loam	CP	7.7	Rainfed/Tile	NO_3
34	Lawlor et al., 2011	IA	Corn	Clay loam	CP	7.7	Rainfed/Tile	NO_3
35	LaHue et al.,2016	CA	Rice	Clay	CP	5.3	Irrigated	N_2O

Table 1. *Cont.*

	Citation	State	Crop	Texture	Tillage	Soil pH	Water Mgmt.	N Losses Monitored
36	Linquist et al., 2015	AR	Rice	Silt loam	CP	Unk	Irrigated	N_2O
37	Maharjan and Venterea 2013	MN	Corn	Silt loam	CP	Unk	Rainfed	N_2O
38	Mitchell et al., 2013	IA	Loam	Corn	NT	6.4	Rainfed	N_2O
39	Mosier et al., 2006	CO	Corn	Clay loam	CP, NT	7.7–7.8	Irrigated	N_2O
40	Nash et al., 2012	MO	Corn	Silt loam	NT, ST	6.2	Irrigated	N_2O
41	Omonode and Vyn 2013	IA	Corn	Silt loam	CP, NT	Unk	Rainfed	N_2O
42	Omonode and Vyn 2019	IN	Corn	Silty clay loam	NT, ST, MP, CP	Unk	Rainfed	N_2O
43	Omonode et al., 2015	IN	Corn	Silty clay loam	CP, NT	6.1	Rainfed/Tile	N_2O
44	Parkin et al., 2016	IA	Corn	Silty clay loam, loam	NT	Unk	Rainfed/Tile	N_2O
45	Pittelkow et al., 2013	CA	Rice	Clay	CP	6.2	Irrigated	N_2O
46	Prunty and Greenland 1997	ND	Potato, Corn	Loamy fine sand	CP	Unk	Irrigated	NO_3
47	Randall and Vetsch 2005	MN	Corn	Clay loam	CP	Unk	Rainfed	NO_3
48	Randall et al., 2003	MN	Corn	Clay loam	CP	Unk	Rainfed	NO_3
49	Sexton et al., 1996	MN	Corn	Sandy loam	CP	Unk	Irrigated	NO_3
50	Steusloff et al., 2019	MO	Corn	Silt loam	CP	6.9, 5.6	Rainfed	N_2O
51	Sistani et al., 2011	KY	Corn	Silt loam	NT	5.8	Rainfed	N_2O
52	Smith et al., 1982	LA	Rice	Silt loam	CP	6.0	Irrigated	N_2O
53	Sogbedji et al., 2000	NY	Corn	Clay loam, Loamy sand	CP	Unk	Rainfed	NO_3
54	Thapa and Chatterjee 2017	MN	Spring wheat	Silt loam	CP	8.1	Rainfed	NH_3, N_2O
55	Thapa et al., 2015	MN	Spring wheat	Silt loam	CP	8.4	Rainfed	NH_3, N_2O
56	Thornton and Valente 1996	TN	Corn	Silt loam	NT	5.75	Rainfed	N_2O
57	Thornton et al., 1996	TN	Corn	Silt loam	NT	6.6	Rainfed	N_2O
58	Toth and Fox 1998	PA	Corn	Silt loam	CP	6.2	Irrigated	NO_3
59	Venterea et al., 2010	MN	Corn	Silt loam	CP	5.2–5.8	Rainfed	N_2O
60	Vetsch et al., 2019	MN	Corn	Clay loam	CP	Unk	Rainfed/Tile	NO_3
61	Walters and Malzer 1990	MN	Corn	Sandy loam	CP	5.7	Irrigated	NO_3
62	Zhu and Fox 2003	PA	Corn	Silt loam	NT/CP	6.1	Rainfed	NO_3

Unk—Unknown; Tillage practice: CP—Chisel plow; ST—Strip tillage, NT—No-tillage; N losses: N_2O—denitrification, NH_3—volatilization, NO_3—leachingMain 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 CN_2O, CNO_3^-, and 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 N_2O, NH_3, and 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 CN_2O (n = 404), CNO_3^- (n = 358), and 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 N_2O fluxes ranged between 0 and 30 kg N_2O-N ha^{-1} yr^{-1} [37]. Previous estimates of 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 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}).

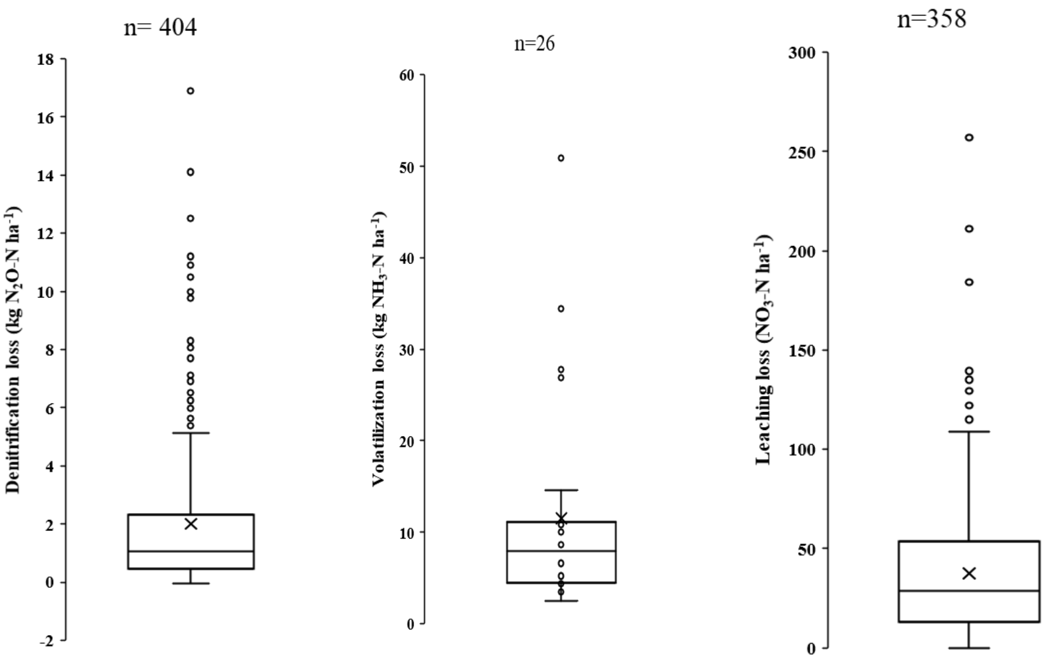

Figure 1. Extent of cumulative nitrogen losses (kg N ha^{-1}) during growing season from non-leguminous field crops, generated from data published in peer-reviewed manuscripts.

Reported cumulative N losses for different states were presented in Table 2. For CN_2O, maximum number of observations (*n* = 100, 25%) was found within the Colorado state. The highest average value of CN_2O (6.62 kg N ha^{-1}) was observed from the Tennessee state; however, only six observations were reported. The lowest average value of CN_2O was observed from Louisiana, whereas the highest maximum value was detected in the Illinois state. The spatial distribution of N_2O sources closely mirrors data on fertilizer application with particularly large N_2O 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_2O-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_2O and CNO_3^- (Table 3). Fertilizer N application rate can explain 38% and 27% of the variability in CN_2O and CNO_3^-, respectively. Fertilizer N rate had a positive effect on both area- and yield-scaled N_2O and NO_3^- losses [2]. A 30% increase in fertilizer-N rate increased annual NO_3^- leaching by 56%, while corn yield increased by only 1% [42]. In Iowa, to achieve an average NO_3^- concentration less than 10 mg L^{-1} in subsurface drainage, the N application rate for corn would need to be less than 112 kg N ha^{-1}, but the current rate ranged from 112 to 168 kg N ha^{-1} [29]. Within the corn production system, linear regression indicates that each unit rise in fertilizer N application rate results in an N_2O-N loss of 0.01 kg N_2O-N ha^{-1} and leaching loss of 0.12 kg NO_3-N ha^{-1} (Figure 2).

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.

Variables		Denitrification	Leaching	Volatilization
N rate	*r*	0.38	0.27	0.09
(kg N ha^{-1})	Pr > |*r*|	<0.001	<0.001	0.66
	n	399	356	26
Crop yield	*r*	−0.015	0.12	0.66
(Mg ha^{-1})	Pr > |*r*|	0.80	0.02	0.01
	n	305	349	14
Water input (mm)	*r*	0.31	0.29	−0.39
	Pr > |*r*|	<0.001	<0.001	0.09
	n	348	308	20
SOM (g kg^{-1})	*r*	0.44	−0.08	−0.61
	Pr > |*r*|	<0.001	0.17	0.001
	n	340	251	24
Clay (g kg^{-1})	*r*	−0.42	0.06	0.55
	Pr > |*r*|	<0.001	0.60	0.03
	n	233	71	16
pH	*r*	−0.21	−0.07	−0.65
	Pr > |*r*|	0.001	0.34	0.001
	n	337	163	26
	r	−0.23	0.03	−0.72
CEC ($Cmole^+$ kg^{-1})	Pr > |*r*|	0.007	0.83	<0.001
	n	135	41	24

Influences of fertilizer-N source on N losses are presented in Table 4. Most of the CN_2O and CNH_3 observations were made on urea application, and urea ammonium nitrate (UAN) was the most popular for the CNO_3^- observations. The highest average CN_2O and CNO_3^- values were observed with ammonium nitrate (AN) application. The application of anhydrous NH_3 had the highest maximum CN_2O. The application of anhydrous NH_3 lost 12.3 kg CN_2O ha^{-1} or 7.33% of applied N, almost double of urea application (6.34 kg CN_2O ha^{-1} or 3.77% of applied N) [43]. Applications of nitrification or both urease and nitrification inhibitors reduced CN_2O values, but the ESN was not effective in reducing CN_2O. The application of ESN delayed the N_2O flux peak by 3 to 4 wk compared with other N sources, but CN_2O did not differ significantly [44]. ESN was not effective in reducing N_2O 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 [$(NH_4)_2SO_4$] > 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].

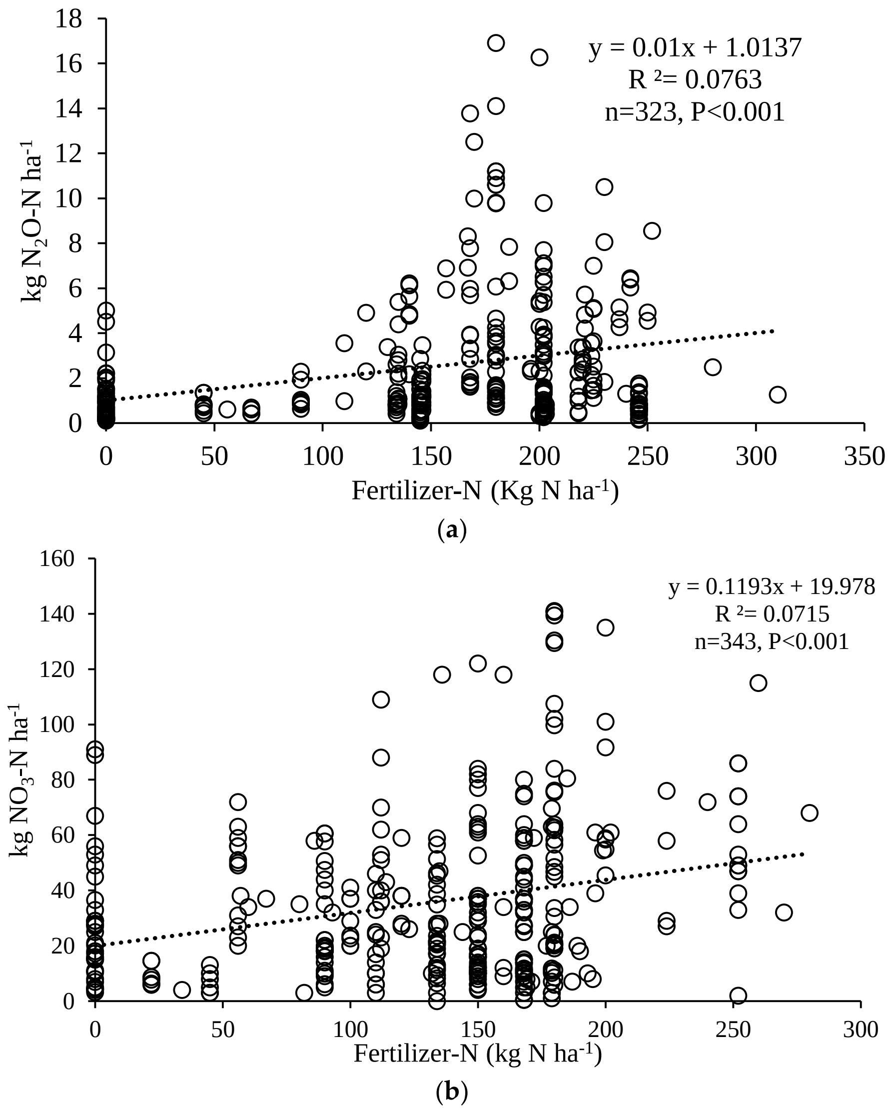

Figure 2. Linear regression relationship between fertilizer N application rate (kg N ha^{-1}) and (**a**) cumulative nitrous oxide flux (kg N_2O-N ha^{-1}) and (**b**) leaching loss of nitrate (kg NO_3-N ha^{-1}) within corn production system.

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 N_2O-N 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 NO_3-N ha^{-1})			
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 NH_3-N ha^{-1})			
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 NH_3; 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 CN_2O values. The most common application methods, broadcast and incorporation, and banding, have similar average and maximum CN_2O losses. Broadcast fertilizer, in comparison to injecting or banding, reduced overall N_2O emissions by 25–33%. The banding of fertilizer-N had the highest average and maximum amount of CNO_3^- values, followed by broadcast and broadcast and incorporation, and then injection [2]. Deep-banded urea had significantly higher soil NO_3^--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 CNH_3 values. The placement of N fertilizers at 3–5 cm below the soil surface reduces the risk of NH_3 volatilization because it reduces the NH_3/NH_4^+ 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 NH_3 before freeze-up increased N_2O 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 CNO_3^- 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 CNH_3 value split between fall and spring. When fertilizer applied in summer, with high soil temperature and low soil moisture contents, NH_3 volatilization tended to increase [1]. On the contrary, the researcher found that CNH_3 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_2O-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_2O-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_2O loss of 2.52 Kg N_2O-N ha^{-1}, followed by potato (1.02 Kg N_2O-N ha^{-1}) and spring wheat (0.98 Kg N_2O-N ha^{-1}). The rice production system had the least average CN_2O, and it showed a negative minimum value. Due to inundation in wetland rice, N_2O is consumed before being released into the atmosphere [18]. Potato with winter rye in rotation had the highest average and maximum CNO_3^- losses. 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_2O-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	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	Corn	6	16.32	5.25	50.9
Spring wheat	Soybean	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_2O-N ha^{-1}) and maximum (16.9 kg N_2O-N ha^{-1}) CN_2O than under no-tillage (1.91 and 16.3 kg N_2O-N ha^{-1}, respectively). One study [20] concluded no clear positive or negative effect of tillage on denitrification. However, in Indiana, reduced N_2O 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].

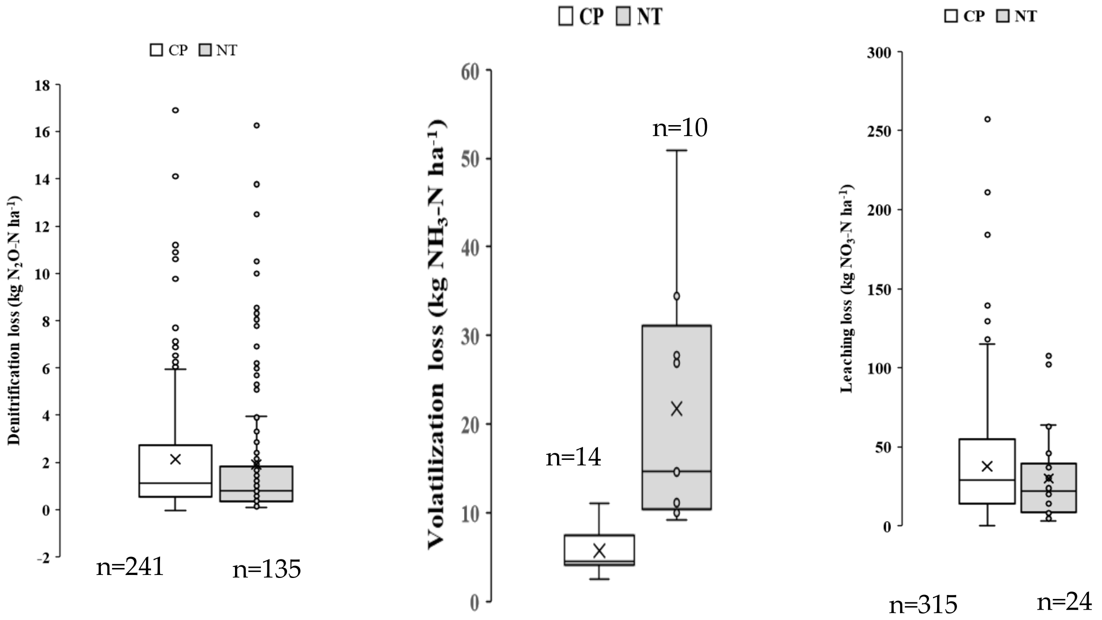

Figure 3. Nitrogen losses (kg N ha^{-1}) as influenced by chisel (CP) and no-tillage (NT) practices.

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_2O was the highest from fields under subsurface drained conditions, and the average value of CN_2O was lower under irrigated condition than soils under rainfed and subsurface drained conditions. Denitrification is strongly affected by water-filled porespace, and combined N_2O and N_2 losses were greater in wetter soils [20]. For leaching loss, the average and maximum values of CNO_3^- 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 CNH_3 than irrigated soils. Another study observed the greatest amount of NH_3 loss (60% of applied N) occurred when no irrigation was applied, and NH_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_2O and CNO_3^- losses (Table 3).

Table 8. Effect of water management practices on N losses (kg N ha^{-1}).

Water Mgmt.	*n*	Mean	Minimum	Maximum
	Denitrification loss (kg N_2O-N ha^{-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_3-N ha^{-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_3-N ha^{-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_2O 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_2O 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_2O-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_2O loss is −0.173 × (CEC) + 0.013 × (clay content) + 0.008 × (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 × (clay content) + 0.331 × (fertilizer-N rate) + 0.273 × (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, Mississipi, 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_2O from daily N_2O 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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