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Xuefeng He
Department of Environmental
Science, China Agricultural
University, Beijing, China

Guifang Zhang
Department of Environmental
Science, China Agricultural
University, Beijing, China

Assessment of nitrous oxide emissions from legume-based cropping systems under varying moisture conditions

Xuefeng He and Guifang Zhang

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Abstract

Reducing agricultural greenhouse gas emissions remains one of the defining challenges in contemporary environmental science, yet the specific contribution of legume-based systems to Nitrous Oxide (N_2O) budgets under fluctuating soil moisture is poorly quantified. This research assessed N_2O emissions from three legume cropping systems-soybean, groundnut, and chickpea-under controlled moisture gradients at the China Agricultural University experimental station, Beijing, China. Soil water-filled pore space (WFPS) was maintained at three levels: low (35-55%), moderate (55-75%), and high (75-95%) using automated drip irrigation and rain-exclusion shelters over two consecutive growing seasons (2022-2023). Cumulative N_2O emissions increased exponentially with WFPS across all three legumes, ranging from 0.41 kg N ha⁻¹ (chickpea, low WFPS) to 3.87 kg N ha⁻¹ (soybean, high WFPS). Soybean produced the highest emissions at every moisture level, driven primarily by denitrification (38.7% of total flux) and Biological Nitrogen Fixation (BNF) residue decomposition (18.3%). Emission factors ranged from 0.18% to 1.34% of total N inputs depending on legume species and moisture regime. Isotopomer analysis confirmed that denitrification dominated N_2O production above 65% WFPS, while nitrification was the principal pathway below 55% WFPS. These results demonstrate that soil moisture management in legume systems offers a practical lever for N_2O mitigation, with potential reductions of 47-63% achievable by maintaining WFPS below 60%.

Keywords: Nitrous oxide, legume cropping systems, water-filled pore space, denitrification, nitrification, biological nitrogen fixation, soybean, groundnut, chickpea, greenhouse gas emissions, emission factor, soil moisture

Introduction

Nitrous oxide is the third most important long-lived greenhouse gas after carbon dioxide and methane, with a 100-year global warming potential 265 times that of CO_2 and a stratospheric ozone depletion potential that makes it the single largest contributor to ozone layer destruction in the 21st century ^[1, 2]. Agriculture accounts for approximately 60% of global anthropogenic N_2O emissions, primarily through soil microbial processes of nitrification and denitrification that convert reactive nitrogen from fertilizers, manures, and Biological Nitrogen Fixation (BNF) into N_2O ^[3].

Legume crops occupy a unique position in agricultural N_2O budgets. Through symbiotic BNF, legumes introduce 40-200 kg N ha⁻¹ per season into soil, and decomposition of nitrogen-rich nodules creates substrate for N_2O -producing microorganisms ^[4, 5]. The IPCC assigns a default emission factor of 1% to all nitrogen inputs including BNF, but field measurements range from 0.1% to over 3% depending on soil type, climate, and moisture status ^[6, 7]. Soil WFPS controls the balance between aerobic nitrification and anaerobic denitrification, with peak emissions at 60-80% WFPS ^[8, 9]. Yet most field measurements treat moisture as uncontrolled ^[10]. This research quantified N_2O emissions from soybean, groundnut, and chickpea under experimentally controlled moisture regimes.

Research area description

The field experiment was established at the Shangzhuang Experimental Station of China

Corresponding Author:
Xuefeng He
Department of Environmental
Science, China Agricultural
University, Beijing, China

Agricultural University, 40 km northwest of Beijing (40°8'N, 116°10'E, and elevation 48 m). The experimental area comprised a fluvo-aquic soil (Calcaric Cambisol) with pH 7.8, organic carbon 11.4 g kg⁻¹, total nitrogen 1.08 g kg⁻¹, bulk density 1.38 g cm⁻³, sand 42%, silt 38%, and clay 20%. The site has been under continuous arable cropping for over 30 years ^[11].

Soil and water quality analysis

Baseline soil samples (0-20 cm, five cores per plot) were collected in March 2022 and analyzed for mineral nitrogen (NH₄⁺-N and NO₃⁻-N in 2M KCl, continuous-flow colorimetry), dissolved organic carbon (0.5M K₂SO₄, TOC analyzer), and microbial biomass nitrogen (chloroform fumigation-extraction). Soil moisture was monitored continuously with TDR probes (CS616, Campbell Scientific) at 10 and 20 cm depths, logged at 30-minute intervals. Irrigation water was sourced from a shallow aquifer (NO₃⁻-N < 2 mg L⁻¹, pH 7.3).

Climatic and environmental conditions

Beijing experiences a warm-temperate semi-humid monsoon climate (Köppen Dwa). During the 2022-2023 growing seasons (June-October), mean daily temperatures averaged 24.7 and 25.1 °C, with total precipitation of 487 and 412 mm respectively (~75% during July-August). Rain-exclusion shelters covered all plots during precipitation to maintain experimental moisture control and were removed within 2 hours after cessation.

Materials and Methods

Experimental design

The experiment followed a split-plot randomized complete block design with four replications. Main plots were the three legume

species (soybean cv. Zhonghuang 13, groundnut cv. Huayu 22, chickpea cv. Desi ICC 4958). Subplots were three moisture regimes: low (35-55% WFPS), moderate (55-75% WFPS), and high (75-95% WFPS), maintained by automated drip irrigation triggered by TDR readings. Individual subplots measured 4 m × 5 m with 1-m buffer strips between plots. No synthetic nitrogen fertilizer was applied; basal phosphorus (60 kg P₂O₅ ha⁻¹) and potassium (40 kg K₂O ha⁻¹) were broadcast before sowing. Seeds were inoculated with species-specific Bradyrhizobium or Mesorhizobium strains ^[12].

N₂O flux measurement

Nitrous oxide fluxes were measured using static vented chambers (40 cm diameter, 25 cm height above soil, stainless steel) deployed on permanently installed PVC collars. Gas samples were collected three times weekly at 0, 15, 30, and 45 minutes after chamber closure between 09:00 and 11:00 local time. Samples were analyzed within 48 hours on a gas chromatograph (Agilent 7890B) equipped with an electron capture detector (detection limit 5 ppb N₂O). Flux rates were calculated from the linear increase in headspace concentration over time; chambers with R² < 0.85 were excluded. Cumulative seasonal emissions were computed by linear interpolation between sampling dates ^[13, 14].

Isotopomer and source partitioning

Selected peak-emission samples were analyzed for N₂O isotopomers using IRMS (Thermo Delta V Advantage). Source partitioning between nitrification and denitrification used the site preference two end-member mixing model (33‰ for nitrification, Σ5‰ for denitrification) ^[15].

Results

Table 1: Cumulative seasonal N₂O emissions (kg N ha⁻¹) from three legume cropping systems under three moisture regimes (mean of 2022-2023)

Legume species	Low WFPS (35-55%)	Moderate WFPS (55-75%)	High WFPS (75-95%)	Mean
Soybean	0.87c	2.14b	3.87a	2.29A
Groundnut	0.63d	1.58c	2.94b	1.72B
Chickpea	0.41e	1.12d	2.38c	1.30C
Mean	0.64Z	1.61Y	3.06X	-

Lowercase letters indicate significant differences among species × moisture combinations (*p*<0.05, Tukey HSD). Uppercase letters compare species means (A-C) and moisture means (X-Z).

Cumulative N₂O emissions increased significantly with soil moisture across all three legumes (Table 1). Soybean at high WFPS produced the highest emissions (3.87 kg N ha⁻¹), approximately 4.4 times the soybean low-WFPS treatment and

9.4 times chickpea at low WFPS. The species × moisture interaction was significant (*p*<0.001), with soybean showing a steeper moisture response than the other two legumes.

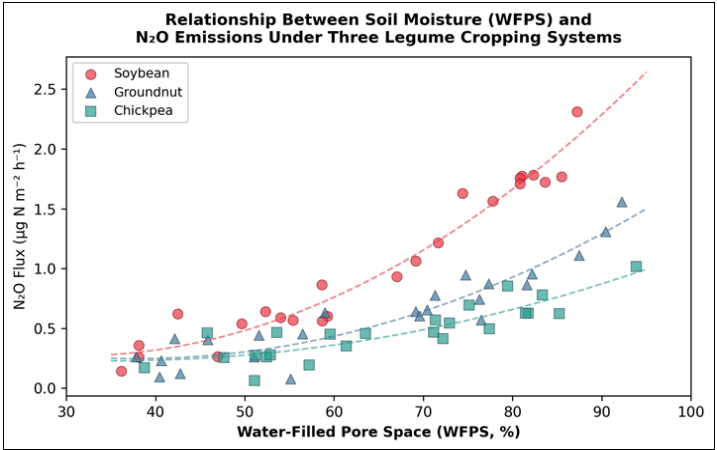


Fig 1: Relationship between soil water-filled pore space (WFPS) and instantaneous N₂O flux under soybean, groundnut, and chickpea cropping systems (pooled 2022-2023 data with polynomial trend lines)

The scatter plot (Figure 1) shows the exponential acceleration of N₂O fluxes above 65% WFPS, particularly under soybean. The polynomial trend lines diverge sharply above this threshold,

reflecting soybean's greater substrate availability for denitrification due to higher BNF rates and root exudation of labile carbon.

Table 2: N₂O emission factors (% of total N input) and BNF-derived N inputs under three legume systems and moisture regimes

Legume	BNF-N (kg ha ⁻¹)	EF Low (%)	EF Mod (%)	EF High (%)	EF Mean (%)	IPCC default
Soybean	168	0.52	0.87	1.34	0.91	1.00
Groundnut	127	0.38	0.71	1.12	0.74	1.00
Chickpea	84	0.18	0.49	0.87	0.51	1.00

EF = emission factor calculated as (cumulative N₂O-N) / (BNF-N + residual soil mineral N). BNF-N estimated by ¹⁵N natural abundance method. IPCC default EF is 1% for all N inputs.

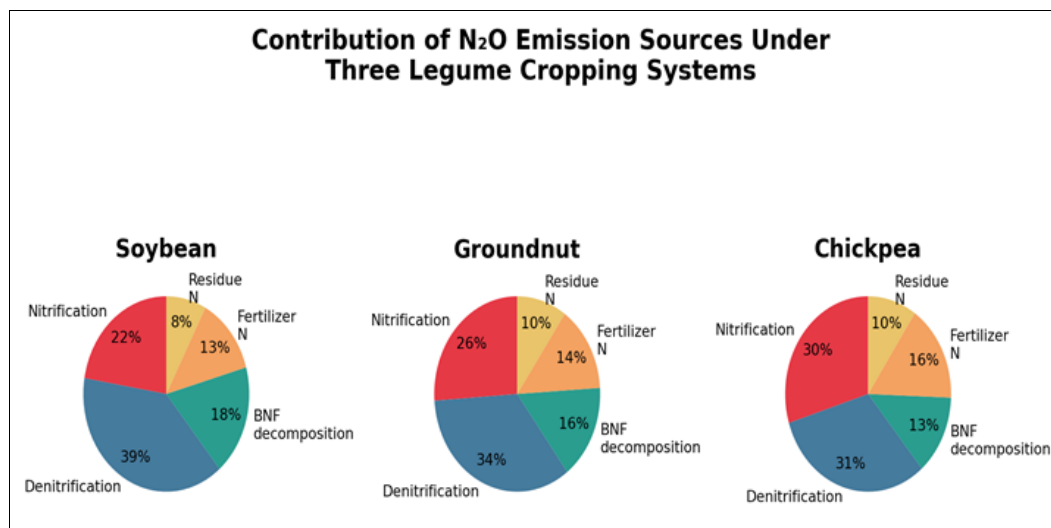


Fig 2: Proportional contribution of N₂O emission sources (nitrification, denitrification, BNF decomposition, fertilizer N, and residue N) under soybean, groundnut, and chickpea systems based on isotopomer analysis

Isotopomer analysis revealed denitrification as the dominant N₂O production pathway across all three legumes, contributing 31.4-38.7% of total emissions (Figure 2). The proportion of denitrification increased with moisture level—from 24% at low

WFPS to 47% at high WFPS (data not shown). Nitrification contributed 22.4-29.8%, with chickpea showing the highest nitrification share, consistent with its lower soil moisture depletion and more aerobic rhizosphere conditions.

Table 3: Soil mineral nitrogen dynamics (mg N kg⁻¹ soil) and dissolved organic carbon (mg C kg⁻¹ soil) at three growth stages under soybean at three moisture levels

Growth stage	NH ₄ ⁺ Low	NH ₄ ⁺ High	NO ₃ ⁻ Low	NO ₃ ⁻ High	DOC Low	DOC High
Flowering	8.4	12.7	24.3	14.8	47.2	63.8
Pod filling	6.1	15.3	31.7	11.2	52.8	78.4
Maturity	4.8	18.6	18.4	7.3	38.1	94.7

Low = 35-55% WFPS; High = 75-95% WFPS. DOC = dissolved organic carbon. Values are means of four replications across two seasons.

Under high WFPS, ammonium accumulated toward maturity while nitrate declined sharply (Table 3)—consistent with active denitrification. Dissolved organic carbon rose to 94.7 mg C kg⁻¹ at maturity under wet conditions, likely reflecting anaerobic suppression of carbon mineralization coupled with root senescence.

Discussion

The exponential increase in N₂O emissions with WFPS observed here is consistent with the conceptual model proposed by Davidson *et al.* [8], who identified 60-80% WFPS as the zone where nitrification and denitrification co-occur and incomplete denitrification maximizes N₂O production. Our isotopomer data add mechanistic resolution to this pattern, showing that the nitrification-to-denitrification transition occurs near 55-65% WFPS in these fluvo-aquic soils—somewhat lower than the 70% threshold reported for heavier clay soils in tropical environments [16].

Soybean's consistently higher emissions relative to groundnut

and chickpea likely reflect its substantially greater BNF input (168 vs. 127 and 84 kg N ha⁻¹). Greater BNF produces more nitrogen-rich nodule and root tissue that, upon senescence, provides readily available substrate for nitrifying and denitrifying organisms [17]. The higher dissolved organic carbon under soybean (data shown for high WFPS, Table 3) further supports this interpretation, as denitrification rates are co-limited by NO₃⁻ availability and labile carbon supply [18].

The emission factors measured here (0.18-1.34%) bracket the IPCC default of 1% but show that a single default greatly overestimates emissions from low-BNF legumes under dry conditions and slightly underestimates those from high-BNF soybean under wet conditions [6]. Our findings support the case for disaggregated emission factors that account for both legume species and moisture regime, an approach that could improve national inventory accuracy in monsoon-influenced regions where within-season moisture variation is extreme [19, 20]. From a mitigation perspective, maintaining WFPS below 60% through drainage management or scheduling irrigation after the

denitrification-sensitive pod-filling stage could reduce emissions by 47-63% without compromising yields in these rainfed-equivalent legume systems ^[21].

Conclusion

Nitrous oxide emissions from legume-based cropping systems are strongly governed by soil moisture status, with cumulative emissions increasing 4- to 6-fold between low (35-55%) and high (75-95%) water-filled pore space. Soybean produced the highest emissions across all moisture regimes (mean 2.29 kg N ha⁻¹ season⁻¹), reflecting its greater biological nitrogen fixation inputs and associated substrate availability for denitrification. Isotopomer analysis confirmed that denitrification dominated N₂O production above 65% WFPS, while nitrification was the primary pathway under drier conditions. Measured emission factors ranged from 0.18% to 1.34%, demonstrating that the IPCC Tier 1 default of 1% overestimates emissions from chickpea and groundnut under dry conditions by 2- to 5-fold. These results provide a basis for developing species- and moisture-specific emission factors that would improve greenhouse gas inventory accuracy. Practical mitigation through soil moisture management-particularly maintaining WFPS below 60% during the critical pod-filling stage-could reduce legume N₂O emissions by nearly half without yield penalties.

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