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Synchronizing nitrogen cycling processes reduces agricultural nitrous oxide and ammonia emissions

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Mitigating reactive nitrogen losses is essential for sustainable agriculture. However, predicting the benefits of substituting synthetic fertilizers with organic amendments remain unreliable because conventional approaches treat soil nitrogen processes in isolation. Here, we adapt a synchrony metric from community ecology to quantify the coordination among nitrogen processes. Using 2,235 global paired observations (organic vs. synthetic), we find that the synchrony metric predicts nitrous oxide (N_2O) and ammonia (NH_3) emissions more accurately than individual processes alone. Specifically, synchrony deviations in nitrification and denitrification account for half of global N_2O variability, while synchrony deviations in mineralization and immobilization explain over one-third of NH_3 variability. Projections indicate that leveraging organic substitution could achieve the greatest N_2O reductions in European croplands (−40.7%) and the highest NH_3 mitigation in Africa croplands (−46.1%). These findings establish process synchrony as a mechanistic framework for improving nitrogen gas loss models and inform targeted organic amendment strategies.

Reactive nitrogen gas emissions, particularly nitrous oxide (N_2O) and ammonia (NH_3), are driving the transgression of the planetary boundaries for biogeochemical nitrogen flows[1], posing severe threats to environmental health and human well-being[2]. N_2O is a potent greenhouse gas with a long atmospheric residence time[3], while atmospheric NH_3 serves as a $PM_{2.5}$ precursor for exacerbating respiratory diseases[4], and redeposited NH_3 perturbs biodiversity[5]. Croplands are the dominant source, contributing to 58% of anthropogenic N_2O and 48% of NH_3 emissions, equivalent to 3.8 Tg N yr^{-1} and 28 Tg N yr^{-1} worldwide, respectively[6,7], primarily driven by synthetic fertilizer application. Accurately predicting reactive nitrogen gas losses from croplands under contrasting management is therefore critical for informing climate change mitigation measures and the transition to sustainable agriculture, yet contemporary models exhibit limited predictive power. Although existing models such as DNDC (DeNitrification-DeComposition) explicitly incorporate key

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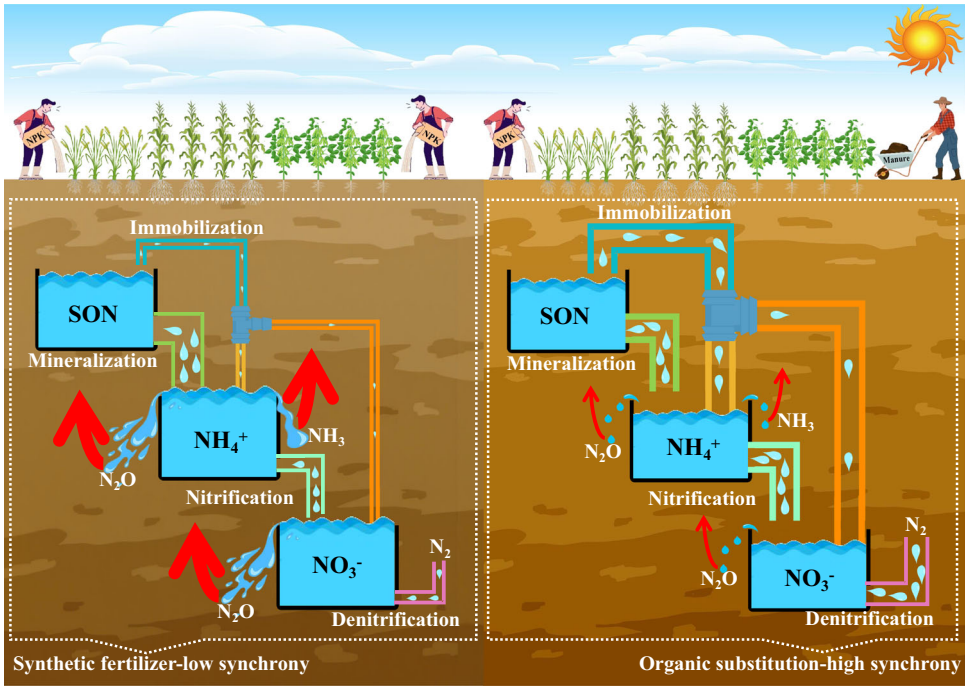

Fig. 1 | Conceptual diagram illustrating how synchrony among soil nitrogen transformations regulates reactive nitrogen gas losses. Synchrony is an emergent property of four nitrogen processes, including mineralization, immobilization, nitrification, and denitrification. Heightened synchrony in soil nitrogen transformations may reduce the reactive nitrogen gas losses from croplands. A theoretical example is shown under synthetic (left) and organic (right) fertilizer application. Pipe diameters represent nitrogen process rates, while the number and size of water droplets indicate the amount of nitrogen transferred. SON, soil organic nitrogen.

nitrogen cycling modules, including mineralization, nitrification, and denitrification, their predictive power for N_2O emissions at large spatial scales remains weak ($R^2 = 0.17$), arguably due to oversimplified representations of nitrogen cycling[8,9]. N_2O production is a product of the microbial processes of nitrification and denitrification, while NH_3 dynamics depend primarily on the balance between mineralization and immobilization. In both cases, synchrony among nitrogen processes regulates substrate availability[10], and it is the balance between soil nitrogen transformations—not isolated reactions—that is expected to improve predictions of reactive nitrogen gas emissions.

Integrating soil nitrogen processes could improve the predictive accuracy of reactive nitrogen gas emissions[11]. Nitrogen transformations are inherently interdependent, linked through shared substrates and feedback[12,13]; omitting these interactions among soil nitrogen processes[14,15] may thus introduce systematic biases in projections. However, a practical method for quantitatively capturing the dynamic coordination of multiple nitrogen processes at scales applicable to agriculture systems is still lacking[16]. Addressing this gap is essential for developing a comprehensive framework for predicting reactive nitrogen gas emissions under agricultural practices, such as organic substitution for synthetic fertilizers. Here, we propose a metric, 'nitrogen process synchrony', to evaluate the coordination among soil nitrogen processes (Fig. 1). The concept was originally developed in community ecology to quantify the relative importance of species' independent responses to exogenous factors compared to the contribution of niche differentiation and competitive dynamics[17]. We extend the synchrony concept to the coordinated responses of soil nitrogen transformations under management change. Here, synchrony is an emergent property of four nitrogen processes (denitrification, nitrification, immobilization and mineralization) and reflects the degree of coordination among process responses to a given management treatment. Theoretically, higher synchrony optimizes nitrogen flows, minimizing the accumulation of intermediate products and thereby reducing N_2O and NH_3 emissions (Fig. 1)[18,19].

Organic substitution for synthetic fertilizer is practiced widely across global croplands, yet its effect on reactive nitrogen gas losses through changing nitrogen cycling synchrony remains unclear. The inputs of exogenous organic matter under organic substitution can stimulate microbial activity and accelerate soil nitrogen processes[20]. However, conflicting relationships between nitrogen process responses and reactive nitrogen gas emissions have been reported under organic substitution. Some studies found that increased N_2O and NH_3 emissions were positively related to nitrification and nitrogen mineralization rates[15,21], while some studies reported decreased reactive nitrogen gas emissions despite elevated nitrogen process rates[22,23]. The synchrony metric of soil nitrogen processes may provide an opportunity to reconcile these apparently contradictory findings.

To quantify the mitigation of N_2O and NH_3 emissions following the substitution of synthetic fertilizer by organic fertilizer across global croplands, we compiled 2235 paired observations across 210 experimental sites to address three specific questions: (1) How does nitrogen cycling synchrony change under organic substitution compared with synthetic nitrogen fertilization? (2) To what extent do changes in the synchrony metric affect reactive nitrogen gas losses? (3) How do environmental forcings modulate nitrogen cycling synchrony under organic substitution? Given the interactions among nitrogen cycling processes through substrate flow, we hypothesized that organic substitution would improve nitrogen cycling synchrony compared with synthetic fertilization (H_1), and that the synchrony metric would outperform individual nitrogen processes in characterizing reactive nitrogen gas emissions (H_2).

Results

Reactive nitrogen gas losses and soil quality responses under organic substitution

Reactive nitrogen gas losses were reduced under organic substitution (including manure, biochar, straw and soil conditioner) compared with conventional fertilization (Fig. 2a). Specifically, N_2O emissions

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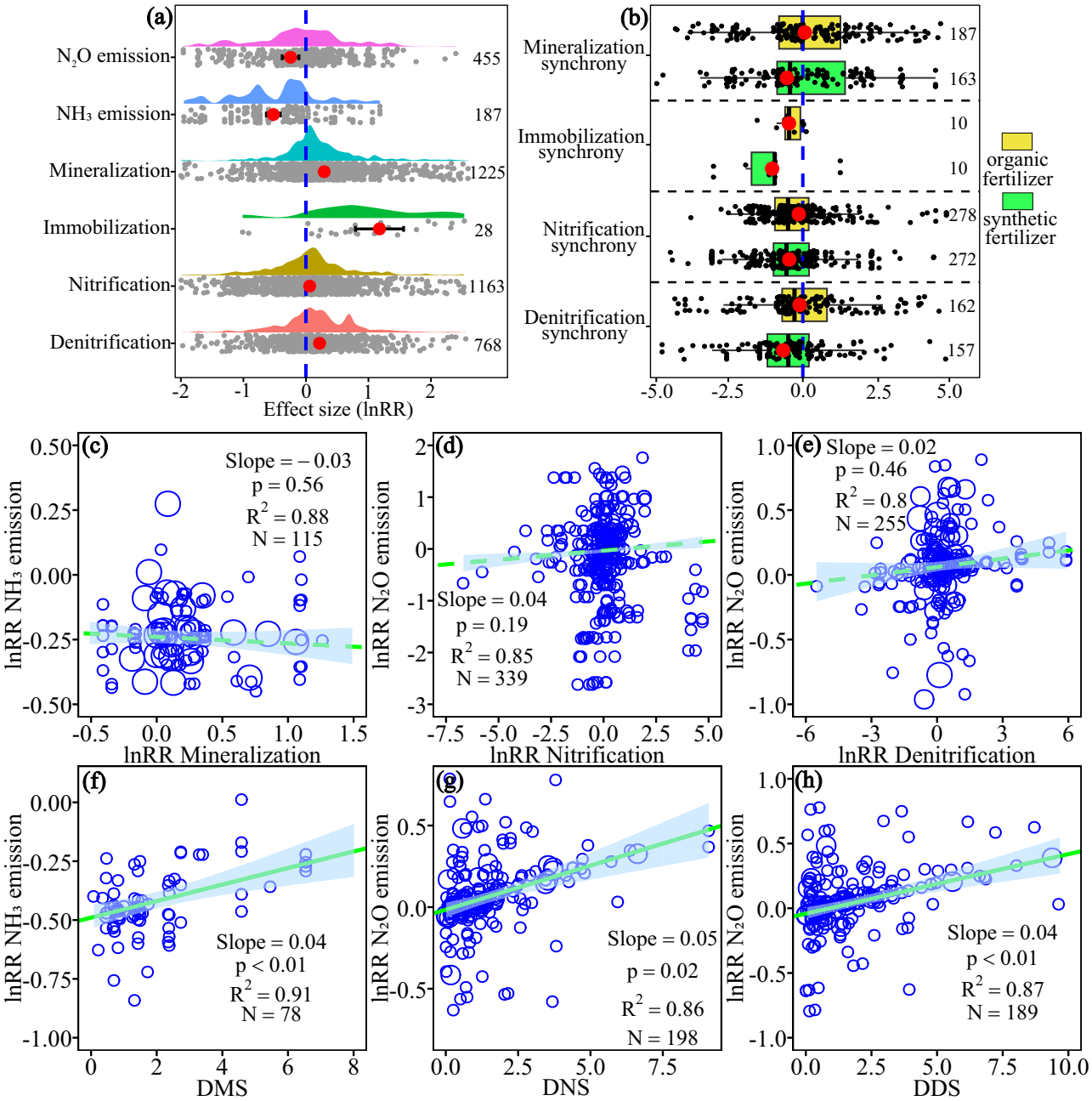

Fig. 2 | Changes in reactive nitrogen gas emissions and nitrogen processes under organic substitution (**a**) and comparison of synchrony of four nitrogen processes between organic substitution and synthetic fertilizer (**b**), as well as bivariate relationships of reactive nitrogen gas emissions against nitrogen processes (**c**–**e**) and synchrony deviations of nitrogen processes (**f**–**h**). In **a**, dots with error bars are the mean values ±95% confidence intervals. The vertical dashed line denotes a zero reference, and the response ratios differed significantly from zero when the 95% confidence intervals did not overlap with the zero reference. Black points represent individual observations. Numbers to the right of each dot are the sample sizes. In **b**, green boxplots are the synchrony of nitrogen processes under synthetic fertilizer relative to a no fertilizer control, and yellow boxplots are the synchrony of nitrogen processes under organic substitution. Black points represent individual observations. The center line indicates the median, box limits represent the 25th and 75th percentiles, and whiskers extend to the most extreme observations within 1.5 times the interquartile range. The vertical dashed line denotes absolute synchrony, red dots indicate mean values, and numbers to the right of each boxplot indicate sample sizes. In **c**–**h**, lines are the slopes ±95% confidence intervals from the linear mixed-effects models. Circles sizes stand for replicate number from 3 to 24. DMS is synchrony deviation of mineralization, DNS is synchrony deviation of nitrification, DDS is synchrony deviation of denitrification, lnRR NH_3 emission is the effect size of NH_3 emission under organic substitution, lnRR N_2O emission is the effect size of N_2O emission under organic substitution. *N*, the number of observations in (**c**–**h**).

decreased by 21.8% (95% CI: −31.6% to −10.6%; $p < 0.001$) and NH_3 emissions lowered by 40.6% (95% CI: −46.9% to −33.5%; $p < 0.001$) under organic substitution. The reductions in N_2O and NH_3 emissions were pronounced across most organic substitution types, except for substitution of urea with manure or organic soil conditioners (Fig. S1). Organic substitution also improved soil quality (Fig. S2a). Soil organic carbon and total nitrogen contents increased by 36.3% (95% CI: 33.0%–39.6%; $p < 0.001$) and 17.8% (95% CI: 15.1%–20.4%; $p < 0.001$), respectively, relative to synthetic fertilization. Microbial biomass carbon and nitrogen increased by 47.4% (95% CI: 40.0%–55.2%; $p < 0.001$) and 29.1% (95% CI: 24.3%–34.2%; $p < 0.001$), respectively. In addition, soil pH significantly increased by 8.7% (95% CI: 8.0%–9.5%; $p < 0.001$). Finally, organic substitution supplemented soil available nitrogen; e.g., ammonium and nitrate contents increased by 11.8% (95% CI:

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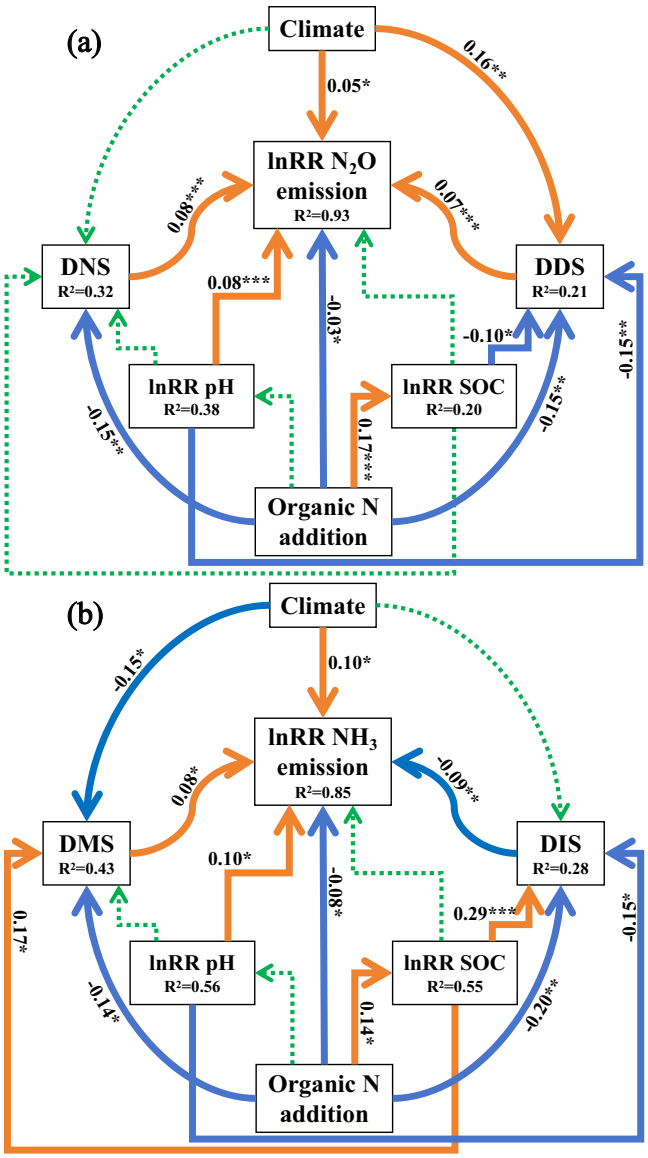

Fig. 3 | Multiple drivers of N_2O (**a**) and NH_3 (**b**) emissions under organic substitution. Orange solid lines indicate significantly positive relationships, blue solid lines indicate significantly negative relationships, and green dashed lines indicate non-significant relationships. Numbers adjacent to lines are standardized coefficients. R^2 values indicate the proportion of variance explained for each endogenous variable. DMS is synchrony deviation of mineralization, DIS is synchrony deviation of immobilization, DNS is synchrony deviation of nitrification, and DDS is synchrony deviation of denitrification. lnRR N_2O emission is the effect size of N_2O emission under organic substitution; lnRR NH_3 emission is the effect size of NH_3 emission under organic substitution. lnRR pH is the effect size of pH under organic substitution. lnRR SOC is the effect size of soil organic carbon under organic substitution. Climate represents a composite climatic variable comprising mean annual temperature and mean annual precipitation. Organic N addition represents the organic nitrogen addition rate. *$p < 0.05$; **$p < 0.01$; and ***$p < 0.001$.

7.5%–16.3%; $p < 0.01$) and 13.5% (95% CI: 9.8%–17.4%; $p < 0.05$), respectively.

Soil nitrogen processes showed differential responses under organic substitution compared with synthetic fertilization (Fig. 2a). Soil nitrogen mineralization rate significantly increased by 34.0% (95% CI: 28.1–40.1%; $p < 0.001$), nitrification rate increased by 6.2% (95% CI: 0.5–12.2%; $p = 0.03$), and denitrification rate increased by 24.4% (95% CI: 15.9–33.6%; $p < 0.001$). Notably, the increase in the immobilization rate under organic substitution was the most pronounced, rising by 2.24-fold (95% CI: 120.7–377.3%; $p < 0.001$). Changes in individual nitrogen processes did not explain the reductions of reactive nitrogen gas losses. Specifically, the effect sizes of NH_3 emissions were not correlated with mineralization (Fig. 2c, $p = 0.56$), and the effect sizes of N_2O emissions were not significantly correlated with nitrification (Fig. 2d, $p = 0.19$) and denitrification (Fig. 2e, $p = 0.46$).

Organic substitution yielded synchrony metrics closer to the ideal status (zero value) compared with conventional fertilization (Fig. S2b), and the synchrony metrics of mineralization, immobilization, nitrification, and denitrification improved by 87.0%, 55.2%, 69.6%, and 83.6%, respectively. Reactive nitrogen gas losses were attributed to the synchrony metrics under organic substitution. NH_3 emissions were positively correlated with the DMS (Fig. 2f, $p = 0.04$, slope <0.01). Similarly, N_2O emissions were positively correlated with the DNS (Fig. 2g, $p = 0.02$, slope = 0.05) and DDS (Fig. 2h, $p < 0.01$, slope = 0.04). Quadratic mixed-effects models revealed no significant quadratic terms, indicating that relationships between synchrony deviations and reactive nitrogen gas losses were linear (Fig. S3). Analyses preserving synchrony deviations further showed that reactive nitrogen gas losses declined with deviations approaching zero (Fig. S4). In parallel, Loreau's synchrony metric revealed consistent relationships, e.g., the effect sizes of N_2O emissions tended to decrease with the gradual improvement in the synchrony of nitrification and denitrification, respectively (Fig. S5).

Subgroup analyses revealed positive relationships between synchrony deviations of nitrogen processes and reactive nitrogen gas losses across organic substitution types and environmental conditions (Fig. S6 and response Table S1). Specifically, increased NH_3 emissions was associated with elevated DMS, while increased N_2O emissions were associated with elevated DNS and DDS. These relationships remained robust when nitrogen process synchrony was quantified using alternative indicators, including process rates, functional gene abundance, and enzyme activity (Fig. S7).

Synchrony changes upon organic substitution depend on environments

Synchrony deviations were sensitive to climate (Fig. S8), indicating that the potential benefits of organic substitution were context specific. DMS and DNS increased (both $p < 0.05$) while DDS decreased in croplands with high mean annual temperature under organic substitution. DMS, DNS, and DDS lowered in croplands with high mean annual precipitation (all $p < 0.05$). DIS exhibited the same tendency as DMS and DNS in response to climate conditions, as these processes are aerobic, although the bivariate relationships were not significant.

Synchrony deviations also depended on soil properties (Fig. S9). As a result of organic substitution practices, DMS increased with soil pH (Fig. S9a, $p = 0.01$, slope = 0.19), while it decreased in soils with high organic carbon content (Fig. S9b, $p = 0.03$, slope = − 0.03) and total nitrogen content (Fig. S9c, $p = 0.02$, slope = − 0.70). Meanwhile, the relationships of DNS and DDS with soil properties (e.g., soil pH, organic carbon content, and total nitrogen content) were analogous overall (Fig. S9g–l). By comparison, the changes of DIS did not exhibit significant correlations with soil properties (Fig. S9d–f).

Synchrony deviations in nitrogen cycling across croplands generally decreased with greater intensity and longer duration of organic substitution (Fig. S10). DMS, DNS and DDS all significantly declined with increasing organic nitrogen application, substitution ratio, and experimental duration (all $p < 0.05$), whereas DIS show no clear trend across these management gradients. These findings suggest that more intensive and prolonged organic substitution generally enhances nitrogen cycling synchrony. These environmental dependencies remained consistent when synchrony deviations were separately calculated using functional gene abundances or enzyme activities,

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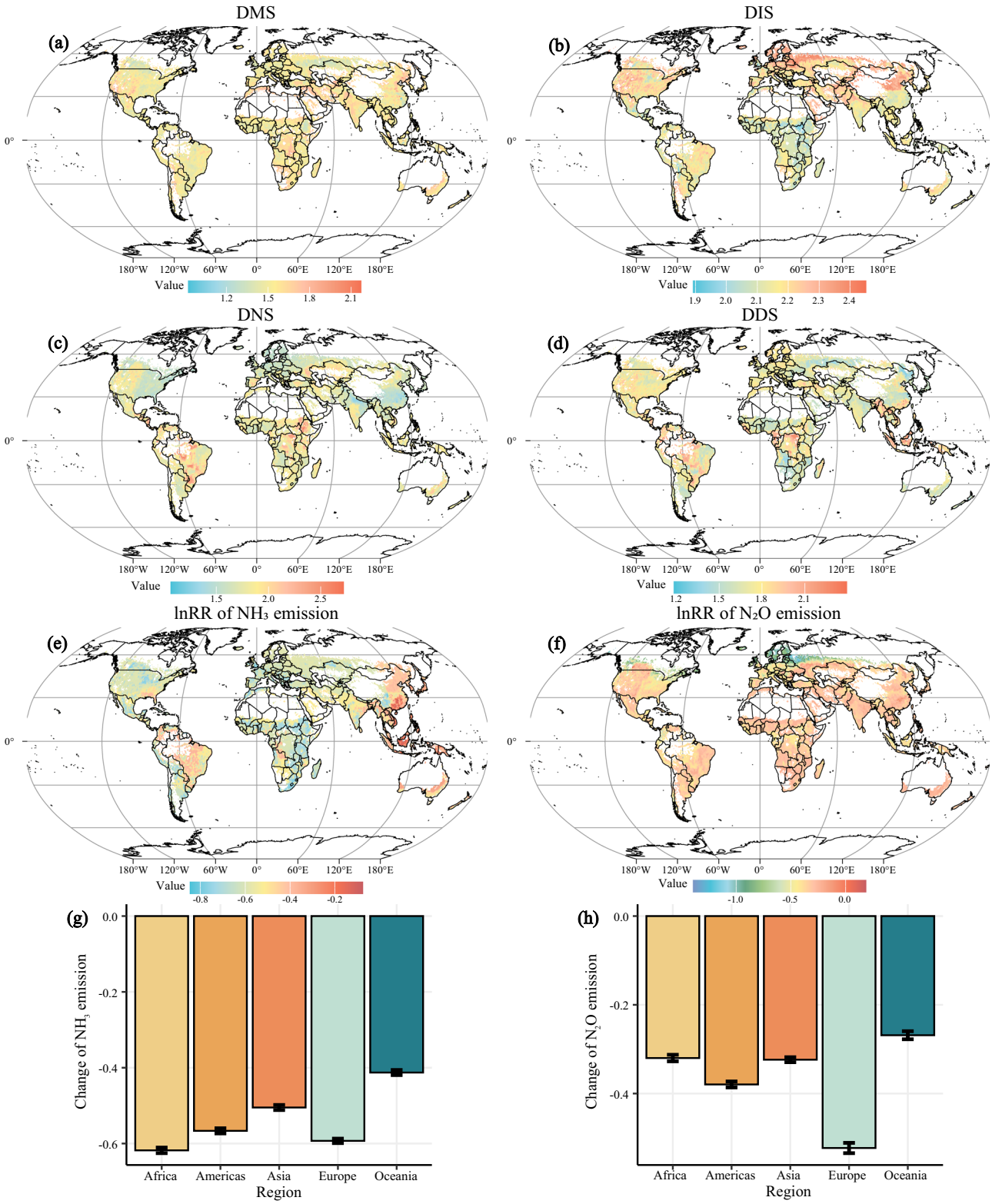

Fig. 4 | Global spatial patterns of synchrony deviations of nitrogen processes and reactive nitrogen gas mitigation potential under organic substitution. Spatial patterns of synchrony deviations in mineralization, immobilization, nitrification, and denitrification (**a**–**d**). Global predictions of effect sizes (lnRR) for agricultural N_2O and NH_3 emissions under organic substitution (**e**, **f**) and weighted averages and standard errors of N_2O and NH_3 emission responses by continent (**g**, **h**). Negative values indicate lower N_2O and NH_3 emissions under organic substitution than only synthetic fertilization.

indicating that the observed patterns were robust across alternative indicators (Fig. S11).

The vital role of synchrony metrics in reactive nitrogen gas emissions

Structural equation modeling (SEM) revealed that increasing organic nitrogen input reduced N_2O emission intensity relative to synthetic fertilizer, which directly accounted for 9.7% of response variation (standardized coefficient = − 0.03, $p < 0.05$). Lower N_2O emissions under organic substitution were also associated with decreased DNS and DDS (standardized coefficients = − 0.14 and −0.15, respectively, $p < 0.01$), because reductions in DNS and DDS often lowered soil ammonium and nitrate concentrations (Fig. S12). The changes in DNS and DDS jointly accounted for approximately 50.0% of the explained variation in N_2O emissions. DNS and DDS responses also depended on soil organic carbon content and/or pH, e.g., elevated soil organic carbon reduced DDS (standardized coefficient = − 0.10, $p < 0.05$). Climate factors explained an additional 16.1% of the variance in N_2O emissions (standardized coefficient = 0.05, $p < 0.05$), primarily via their effects on DDS.

DMS and DIS played pivotal roles in regulating NH_3 emissions under organic substitution (Fig. 3b). Specifically, increasing DMS led to soil ammonium accumulation, which in turn promoted NH_3 emissions (Fig. S12). Changes in DMS and DIS jointly explained 37.8% of the variation in NH_3 emission, with DMS and DIS accounting for 17.8% (standardized coefficient = 0.08, $p < 0.05$) and 20.0% (standardized coefficient = − 0.09, $p < 0.01$), respectively. DMS and DIS had opposite roles in mediating NH_3 emissions; elevated DMS enhanced NH_3 emissions, whereas higher DIS reduced NH_3 emissions. Climate influenced the NH_3 emissions through changing DMS (standardized coefficient = − 0.15, $p < 0.05$). Additionally, soil pH influenced NH_3 emissions and explained 22.3% of the variation (standardized coefficient = 0.10, $p < 0.05$). Organic nitrogen application and soil organic carbon increase exerted a slightly stronger influence on changes in DMS and DIS than on those in DNS and DDS (Fig. 3).

Spatial patterns of synchrony deviation of nitrogen processes and reactive nitrogen gas mitigation under organic substitution

At a spatial resolution of 0.5° × 0.5°, a random forest model was applied to predict changes in synchrony deviations of nitrogen processes (Fig. 4a–d) and reactive nitrogen gas emissions (Fig. 4e–g) based on global climate, soils, and management data. The predicted map of synchrony deviations revealed clear spatial heterogeneity in the coordination of nitrogen transformation processes under organic substitution, providing a process-level context for interpreting regional differences in reactive nitrogen gas mitigation. The simulations indicated that global potential for organic substitution could effectively reduce emissions of both gases. Africa exhibited the most pronounced reduction in NH_3 emissions, given that the minor DMS−DIS difference accelerated ammonium turnover and limits NH_3 volatilization (Fig. 4a, b). European croplands demonstrated better performance in mitigating N_2O emissions relative to other regions, owing to the lower DNS and DDS values (Fig. 4c, d). Overall, organic substitution delivers larger NH_3 than N_2O reductions across global croplands. At the continental scale (Fig. 4g, h), organic substitution reduced NH_3 emissions most markedly in Africa (by 46.1%) and Europe (by 44.2%), with sizeable decreases also in Americas, Asia, and Oceania. N_2O emissions fell markedly as well, led by Europe (by 40.7%) and Americas (by 31.6%), followed by Africa, Asia, and Oceania.

Discussion

Prevailing reductionist approaches, focusing on isolated soil nitrogen processes, fail to capture the dynamics of reactive nitrogen gas losses[24]. Here, we propose a synchrony metric adapted from community ecology[17] to integrate interdependent soil nitrogen cycling processes and better model N_2O and NH_3 emissions (Figs. 2 and 3). Concordant with theoretical expectations, organic substitution enhanced nitrogen cycling synchrony relative to synthetic fertilization (H_1), and synchrony metrics provided stronger explanatory power for reactive nitrogen gas losses than did individual nitrogen processes (H_2). Accordingly, organic substitution reduced N_2O emissions by 21.8% and NH_3 emissions by 40.6% through enhancing synchrony among soil nitrogen cycling processes (Fig. 2). This synchrony perspective offers a mechanistic lens for accurately predicting reactive nitrogen gas losses and refining global cropland nitrogen budgets.

Synchronizing nitrogen processes drives reactive nitrogen gas reductions

Global mitigation of N_2O and NH_3 under organic substitution arises from tighter synchrony among nitrogen transformations, emerging from differential responses of individual processes (Fig. 2), in support of H_2. Although local studies have linked higher denitrification to more N_2O emissions and greater mineralization to more NH_3 emissions[25,26], these relationships often collapse at broad scales[14]. Crucially, our findings reveal that both gases declined even in cases where denitrification and mineralization increased under organic substitution (Fig. 2), highlighting the limits of extrapolating reductionist frameworks across heterogeneous agricultural systems. Models ignoring synchrony predicted a rise in N_2O emissions from croplands under organic substitution[27], directly contradicting the observed 21.8% reduction (Fig. 2).

Synchrony among nitrogen processes may regulate soil inorganic nitrogen concentrations and microenvironments, thereby shaping N_2O and NH_3 emissions. Nitrite, as a key N_2O precursor (yielding 2.1 units of N_2O per unit of nitrite)[28] accumulates when nitrification and denitrification are mismatched, and NH_3 volatilization generally tracks ammonium accumulation[29] that is determined by the balance between mineralization and immobilization[12]. Elevated nitrogen cycling synchrony could accelerate substrate turnover, suppress inorganic nitrogen accumulation, and consequently lower emissions of both gases (Fig. S12). Moreover, maintaining soil pH within an appropriate range is important for regulating nitrogen emissions, given that NH_3 emissions generally increase under alkaline conditions[30], while N_2O production and reduction processes are sensitive to soil acidity and alkalinity[31]. Enhanced nitrogen processes synchrony may also buffer soil pH, thereby lowering N_2O and NH_3 emissions. For example, hydroxyl ions produced during mineralization may be neutralized by hydrogen ions generated during nitrification[10], contributing to pH homeostasis (Fig. S12). Although anammox (optimal at a pH ≈ 8.3 and a temperature range of 30–40 °C)[32] can additionally consume ammonium and modulate N_2O[33,34], its contribution is minor under typical field conditions.

Synchrony of nitrogen cycling processes is improved under organic substitution

Organic substitution synchronizes soil nitrogen processes likely through modulating substrate supply and microbial activities. Organic amendments gradually release nitrogen through mineralization[12], supplying inorganic nitrogen at rates that maintain relatively steady-state concentrations of ammonium and nitrate, whereas synthetic fertilizers create episodic pulses[35] that may overwhelm certain processes. The continuous substrate supply could ensure sustained nitrogen transformations, e.g. nitrogen mineralization and denitrification, respectively[36]. The microbial response is also likely an important element of improved synchrony, given that organic substitution increased microbial biomass carbon and nitrogen by 47.4% and 29.1%, respectively (Fig. S2). This expanded microbial pool increases mineralization rates, since 55–89% of nitrogen originates from microbial turnover[37], and propagates downstream reactions (nitrification, denitrification, and immobilization). Elevated

ammonium concentrations stimulate nitrifier activity in accordance with Michaelis–Menten kinetics[38], while additional labile carbon enhances the activity and abundance of *nirK*- and *nirS*-harbouring denitrifiers, elevating denitrification rates[31,39]. The simultaneous rise in ammonium and nitrate (Fig. S2a) likely strengthens the microbial immobilization capacity[40]. In contrast, conventional fertilization may impose carbon limitation that suppresses heterotrophic activity[41] while promoting an imbalanced dominance of nitrifiers[42]. Collectively, these results support H_1 that organic substitution coordinates interdependent nitrogen transformations, demonstrating that controlled substrate delivery coupled with microbial activation can optimize nitrogen cycling efficiency.

Environmental mediation of nitrogen process synchrony

Soil pH differentially affects the synchrony of nitrogen processes, with higher pH enhancing nitrification and denitrification synchrony while suppressing mineralization synchrony (Fig. S9). This pH-dependent regulation is likely underpinned by different microbial responses. In general, the abundance of bacterial *amoA* and the denitrification genes *nirK* and *nirS* increases with rising pH[43,44], while the copy number of *nagA* encoding *β*-N-acetylglucosaminidase declines[45]. Consequently, nitrification and denitrification rates accelerate as pH rises, while mineralization efficiency diminishes. These pH-mediated changes in microbial traits further modulate nitrogen transformation processes. Ammonia-oxidizing microorganisms reach maximal activity at neutral to alkaline pH[46], whereas the microbial activity associated with mineralization decreases sharply; e.g., microbial growth rates decline to approximately one-fifth when soil pH increases from 4.5 to 8.3[47]. Elevated pH increases both nitrate availability and nitrate reductase activity, creating favorable conditions for denitrification even as it inhibits certain aerobic nitrogen transformations.

Soil organic carbon represents another critical regulator of nitrogen cycling synchrony. Organic substitution increased soil organic carbon content by 36.3% (Fig. S2). The added carbon likely supports nitrifier populations[48], fuels heterotrophic nitrification[49], and supplies substrates for denitrification. Organic matter decomposition releases organic acids and amino acids that activate urease and other enzymes involved in mineralization[50]. Precipitation introduces additional complexity into synchrony patterns (Fig. S8) by altering soil redox conditions. Increased precipitation can result in soil anaerobic conditions[51], suppressing aerobic processes like mineralization and nitrification[52]. Although denitrification typically benefits from diminished oxygen availability[53], extreme precipitation events can leach nitrate, thereby limiting substrate supply and attenuating denitrification[54].

Regional divergence in reactive nitrogen gas mitigation

Organic substitution is predicted to reduce global losses of reactive nitrogen gases, yet the N_2O reduction is disproportionately stronger in European croplands (Fig. 4). This spatial asymmetry arises from three converging factors. First, for most European arable soils, interannual variability in precipitation and soil moisture is low, supporting strong coupling among mineralization, nitrification, and denitrification[55]. Such hydrological stability enhances nitrogen process synchrony (Fig. 4), thereby amplifying the extent to which organic substitution can alter N_2O emissions. Second, soil conditions in Europe provide a favorable basis for lower N_2O, particularly in southern and central regions, where agricultural soils are predominantly neutral to slightly alkaline[56]. Under such soil conditions, microorganisms involved in the nitrogen cycle can maintain relatively high activity[46,57]. As a result, the overall synchrony deviations in nitrogen cycling remains at a low level, especially for DDS (Fig. 4), which effectively reduces N_2O losses. Meanwhile, the long-term practices of organic fertilizer management (e.g., straw incorporation and livestock manure application) not only ensure a steady nitrogen supply but also sustain the activity and functional diversity of microbial communities[58]. These factors may jointly decrease synchrony deviations of nitrogen processes and lower the risk of N_2O emissions.

By comparison, our results indicate that organic substitution may exert the most pronounced mitigation effect on NH_3 emissions from African croplands. Two main mechanisms may explain this outcome. In general, African agricultural soils are generally characterized by low organic matter content and poor nitrogen retention capacity[59]. Such conditions often induce short-lived yet intense ammonium accumulation peaks near the soil surface, thereby triggering substantial NH_3 emissions under synthetic fertilization. In contrast, the slow release of available nitrogen from organic substitution reduces instantaneous accumulation of volatile ammonium at the soil surface[12], thus suppressing NH_3 emissions. Further, the metabolism of heterotrophic microorganisms in African soils can be constrained by insufficient carbon availability[60]. The addition of exogenous organic matter supplies readily available carbon substrates, markedly stimulating heterotrophic microorganism growth and metabolism[61], thereby enhancing the balance between autotrophic and heterotrophic microorganisms involved in nitrogen mineralization and immobilization. Consequently, lower DMS and DIS (Fig. 4) ultimately curb NH_3 losses.

Implications and limitations

Our study establishes nitrogen process synchrony as a fundamental yet previously neglected metric governing reactive nitrogen gas emissions. Current models, although incorporating some nitrogen processes, typically treat these processes as isolated components rather than as interconnected systems with inherent coordination[62,63]. By incorporating synchrony metrics, we provide a framework to reduce the uncertainty of N_2O and NH_3 emission predictions. The synchrony perspective is also useful to identify practical mitigation strategies for reducing reactive nitrogen gas emissions. Conventional single process interventions (e.g. nitrification inhibitor) often yield suboptimal outcomes due to compensatory effects in other nitrogen transformation pathways[64]. In contrast, strategies that enhance overall process synchrony may offer more robust solutions. The synchrony metric emerges as both a diagnostic tool for evaluating fertilization practices and a guiding principle for developing region-specific management policies that account for local environmental conditions.

Several limitations warrant consideration. First, although our dataset encompasses worldwide croplands, the uneven distribution of experimental sites reflects the challenges in compiling comprehensive field data. Nevertheless, the included sites sufficiently represent typical croplands under organic substitution worldwide. Second, enzyme activities and functional gene abundances integrated into the synchrony metric may introduce uncertainties. Synchrony metrics derived from process rates, enzyme activities, and functional gene abundances were all effective predictors of reactive nitrogen gas losses (Fig. S7); nevertheless, process-rate-based synchrony may offer greater predictive power. Future studies would benefit from direct quantification of nitrogen transformation rates to constrain synchrony estimates.

Methods

Data collection

Data were collected from peer-reviewed papers, primarily using two platforms: Web of Science (http://apps.webofknowledge.com) and the China National Knowledge Infrastructure database (CNKI, http://www.cnki.net), with additional literature screening conducted through Google Scholar. The screening keywords were (organic fertilizer OR straw OR biochar OR manure) AND (nitrogen cycle OR nitrification OR denitrification OR mineralization OR immobilization) AND (nitrous oxide OR ammonia). Article screening followed PRISMA guidelines (Fig. S13)[65] and included peer-reviewed papers dated up to November

10, 2024. The criteria for screening were: (1) experiments conducted in agricultural ecosystems that included both synthetic nitrogen fertilizer and organic substitution for synthetic fertilizer, with both treatments receiving equal nitrogen application inputs; (2) organic substitution treatments lasting for at least one crop growing season; and (3) each experiment reported at least one soil nitrogen process, including mineralization, immobilization, nitrification, and denitrification, and/or reactive nitrogen gas emissions, including nitrous oxide or ammonia emissions. To avoid temporal mismatch, nitrogen processes indicators and reactive nitrogen gas emissions were measured only when they were reported from the same site, treatment comparison, and experimental observation period.

Detailed site information was extracted from the peer-reviewed papers, including geographical coordinates, climatic conditions, experimental duration, and management information. Missing climatic data, including mean annual temperature and mean annual precipitation, were supplemented using WorldClim (http://www.worldclim.org)[66]. Soil nitrogen process rates and soil properties, including moisture, bulk density, pH, clay content, organic carbon, total nitrogen, ammonium, nitrate, microbial biomass carbon, and microbial biomass nitrogen, were directly extracted from texts and tables in peer-reviewed papers, while graphical data were digitized using Get-Data software (version 2.2). Because direct measurements of nitrogen transformation rates were limited, functional gene abundance and enzyme activity were used as proxies. To minimize unit differences among variables, all data were converted into natural logarithmic response ratios (lnRR) to represent treatment effects relative to the control. Effect sizes based on gene abundance and enzyme activity were significantly and positively correlated with those derived from nitrogen transformation rates (Fig. S14). Furthermore, the relationships between reactive nitrogen gas losses and synchrony deviations (calculated separately using nitrogen process rate, functional gene abundance, and enzyme activity) were examined; these relationships remained consistent across the different indicators (Fig. S7).

Data overview

The dataset comprised 2235 observations from 210 experimental sites (see Fig. S15 for the geographical distribution), with most sites located in Asia (1796 observations), Europe (173 observations) and North America (47 observations). These sites exhibited a range of climate conditions and soil properties. For example, mean annual temperature, mean annual precipitation, and soil pH ranged from 3.2 to 30.4 °C, 76 to 2497 mm, and 3.5 to 8.9, respectively. Meanwhile, the included observations also spanned a broad range of experimental durations, from single cropping season to more than 50 years (Fig. S16). A total of 675 observations were derived from a 1-year experiment, accounting for approximately 30% of the dataset. To calculate the effect size of each variable, synthetic fertilization served as the control and organic fertilization as the treatment. The organic amendments included straw return, biochar addition, manure addition, and organic soil conditioners (such as mushroom residues). Synthetic fertilizers included ammonium, nitrates, and urea, etc.

Data analyses

A meta-analysis was performed to reveal the impacts of organic substitution on reactive nitrogen gas losses and soil properties. Effect sizes and variances (v_i) were calculated as follows:

$$\mathrm{lnRR} = \ln(X_t/X_c) \tag{1}$$

$$v_i = \frac{S_t^2}{N_t X_t^2} + \frac{S_c^2}{N_c X_c^2} \tag{2}$$

where X_t represents the mean value of one variable under organic substitution, while X_c is the mean value of the variable under synthetic fertilizer application; N_c and N_t are the sample sizes of synthetic fertilizer application and organic substitution, respectively; S_t and S_c are standard deviations of control and treatment, respectively. The weight (w_t) of each observation and the weighted natural logarithm of response ratio (R_+) were estimated were calculated as follows:

$$w_t = \frac{1}{v_i} \tag{3}$$

$$R_+ = \frac{\sum_{i=1}^{m} W_i * \mathrm{lnRR}_i}{\sum_{i=1}^{m} W_i} \tag{4}$$

where i denotes the ith observation and m is the total number of observations. The percentage change for each variable was calculated as:

$$(e^{R_+} - 1) \times 100\% \tag{5}$$

The *'metafor'* package version 4.6.0 in R (version 4.4.1) was used to conduct a mixed-effects meta-analysis. Moreover, a hierarchical mixed-effects meta-analysis with a nested random effects structure (-1| study) was performed, where 'study' represented different experimental cases.

Publication bias was assessed using Egger's test and the fail-safe number, with both analyses performed in the '*metafor*' package version 4.6.0 in R 4.4.1. For each variable, we reported the sample size, Egger intercept, corresponding p value, 95% confidence interval, and fail-safe number for each variable (Table S2). Funnel plots were also generated to visually assess effect-size symmetry and potential small-study effects (Fig. S17). Egger's test revealed potential funnel-plot asymmetry for several variables, including N_2O emission, soil organic carbon, total nitrogen, microbial biomass carbon, microbial biomass nitrogen, ammonium, nitrate, mineralization, and denitrification. Nevertheless, the fail-safe numbers for these variables all exceeded $5n+10$, where n is the number of observations, suggesting that potential publication bias was unlikely to qualitatively alter the main conclusions.

The lnRR of soil nitrogen process were used to calculate synchrony:

$$\sum_{i=1}^{n} \Delta R_i = \Delta R_1 + \Delta R_2 + \ldots + \Delta R_n \tag{6}$$

$$\Delta S_i = \frac{\Delta R_i \times (n-1)}{\sum_{i=1}^{n} \Delta R_i - \Delta R_i} - 1 \tag{7}$$

where ΔR_i is the change in the rate of the i_{th} nitrogen process. ΔS_i is the change in synchrony of the i_{th} process relative to the other nitrogen processes. In Eq. 7, a value of 0 indicates absolute synchrony. Synchrony deviation was calculated as:

$$\text{Deviation from } \Delta S_i = |\Delta S_i| \tag{8}$$

Based on the above equations, linear mixed-effects models were used to examine the following aspects: (1) bivariate relationships between reactive nitrogen gas losses and soil nitrogen process rates, as well as the relationships of reactive nitrogen gas losses against synchrony deviations; (2) the impacts of environmental heterogeneity on synchrony deviations; (3) the influence of experimental duration on synchrony deviations of nitrogen processes; and (4) pairwise relationships among synchrony deviation metrics, soil inorganic nitrogen pools, soil pH, and reactive nitrogen gas losses. In all models, 'study' was viewed as a random effect to take experimental differences into

account, and the number of replicates was used as weights. The analyses were completed using the '*lme4*' package version 1.1-35.5 in R 4.4.1 with maximum likelihood estimation.

To further assess whether reactive nitrogen gas emission responses and their associations with nitrogen process synchrony deviations remained consistent across substitution practices, we conducted subgroup analyses based on organic amendment type. Observations were categorized as straw return, biochar addition, manure addition, or organic soil conditioner application. Within each subgroup, we quantified changes in N_2O and NH_3 emissions under organic substitution and independently examined the relationships between reactive nitrogen gas losses and synchrony deviation metrics using the same linear mixed-effects modelling framework (Fig. S6).

The classical synchrony equation in community ecology[17] was also employed to calculate the synchrony among soil nitrogen processes:

$$\text{Synchrony} = \frac{\sigma_X^2}{\left(\sum_i \sigma_{Xi}\right)^2} \quad (9)$$

where σ_X^2 represents the variance of an individual nitrogen process under the same 'study', while $(\sum_i \sigma_{Xi})^2$ represents the sum of variances of all nitrogen processes under the same 'study' treatment. To further verify the relationship between reactive nitrogen gas losses and synchrony among nitrogen processes (using Eq. 8), we further tested the relationship of reactive nitrogen gas losses against synchrony (using Eq. 9).

Structural equation modeling (SEM) was applied to investigate the direct and indirect effects of environmental variables on reactive nitrogen gas losses through changing synchrony deviation of nitrogen processes. Specifically, two structural equation models were constructed to separately assess multivariate relationships for N_2O and NH_3 emissions. The first SEM focused on the synchrony deviation of nitrification and denitrification, and N_2O emissions. The second SEM evaluated the effects of environmental factors and synchrony deviation of mineralization and immobilization on NH_3 emissions. In both models, 'study' was treated as a random effect to account for variation among studies, and the number of replicates was used as weights. Initial models included all hypothesized causal relationships and were subsequently optimized based on Akaike information criterion (AIC) minimization. The final two structural equation models are eligible, with $p = 0.167$ for the N_2O emission model and $p = 0.297$ for the NH_3 emission model. All SEMs were tested using the '*piecewiseSEM*' package version 2.3.0.1 in R 4.4.1.

Before projections, a global dataset for 12 independent variables were constructed, including mean annual temperature, mean annual precipitation, soil clay and silt content, pH, organic carbon, total nitrogen, the amount of organic nitrogen application (merely organic nitrogen content in total nitrogen application), deviation from mineralization synchrony (DMS), deviation from immobilization synchrony (DIS), deviation from nitrification synchrony (DNS), and deviation from denitrification synchrony (DDS). Climatic factors (e.g., mean annual temperature and precipitation) were obtained from WorldClim (https://worldclim.org/data/worldclim21.html)[66]. The soil properties database was derived from the Global Soil Dataset for Earth System Modelling (http://globalchange.bnu.edu.cn/research/soilw)[67]. The organic nitrogen application was obtained from the National Tibetan Plateau Data Center Third Pole Environment Data Center (https://cstr.cn/18406.11.Terre.tpdc.300446)[68].

The performance of nine machine learning algorithms was compared, including extreme gradient boosting, random forest, gradient boosting machine, support vector machine, recursive partitioning and regression trees, generalized linear, elastic-net regularized generalized linear, neural network, and stepwise regression. Based on ten-fold cross-validation, the random forest model emerged as the optimal choice, as it achieved both relatively high coefficients of determination ($R^2 = 0.37$ for N_2O and 0.72 for NH_3 emissions) and low prediction errors (MAE = 0.08 and 0.10, RMSE = 0.13 for both gases; Fig. S18). Because the hyperparameters of random forest model can substantially influence predictive accuracy, we first tuned these parameters using a grid search procedure. Moreover, the predicted N_2O and NH_3 emissions showed close agreement with the observed values (Fig. S19). Model performance was initially evaluated as the lnRR. To assess whether predictive performance was sensitive to logarithmic transformation, the observed and cross-validated predicted values were back-transformed to the response-ratio scale using RR = exp(lnRR). The R^2, MAE, and RMSE were then recalculated. Performance metrics were robust to this transformation (Table S3 and Fig. S20). Global synchrony deviationdata for nitrogen processes were generated at a 0.5° resolution (Fig. 4).

Finally, to compare the effects of organic substitution on N_2O and NH_3 emissions across regional croplands, the "*rnaturalearth*" package version 1.0.1 in R 4.4.1 was used to obtain country vector data. Global croplands were binned into five regions: Asia, the Americas, Africa, Europe, and Oceania. In each region, the mean and standard deviation of the logarithmic response ratios of N_2O and NH_3 emissions were calculated. Finally, the "*ggplot2*" package version 4.0.2 in R 4.4.1 was used to visualize the emission changes in each region.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The meta-analysis dataset generated in this study have been deposited in the Figshare repository at https://doi.org/10.6084/m9.figshare.33170645[69]. Source data are provided with this paper.

Code availability

The codes have been uploaded to the Figshare repository (https://doi.org/10.6084/m9.figshare.33170645)[69].

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Author contributions

Z.L.L. conceptualized the research. M.F.L. compiled the dataset. M.F.L., Y.Z.Y., and B.B.H. analyzed the data. M.F.L. and Z.L.L. drafted the manuscript. Z.L.L., S.W., J.S., A.C., Q.F.M., and Q.R.L. revised the manuscript. Z.L.L., M.F.L., Y.Z.Y., B.B.H., S.W., J.S., A.C., Q.F.M., Q.R.L., C.L.X., W.L.K., and H.L. contributed to the reviewing of the manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

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