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One Earth

Increasing nutrient inputs risk a surge of nitrous oxide emissions from global mangrove ecosystems

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SUMMARY

We document a substantial increase in global N_2O emissions from mangroves. Based on our analysis of two decades of mangrove N_2O emission studies, we estimate N_2O emission of 0.023 Tg N yr^{-1} from global mangrove ecosystems. N_2O fluxes from mangrove ecosystems are strongly increased by sediment dissolved inorganic nitrogen (DIN) concentration transported from river catchments to coastal waters. Continuing growth of nutrient inputs from anthropogenic sources, i.e. agricultural intensification, excessive fertilizer use and waste water discharge, will appreciably increase DIN loading and consequently global N_2O emission from mangroves. Based on the Millennium Ecosystem Assessment scenarios of riverine DIN inputs into mangrove ecosystems coupled with our estimates of DIN controlled emissions rates, we expect N_2O emission to increase by 20 to 51% by 2030 and 27 to 74% by 2050 compared to estimated emissions in the year 2000. These forecasts underline the urgency of improvements in catchment-scale nitrogen management strategies.

Keywords: mangroves, nitrous oxide, emissions, nutrients, river catchments

INTRODUCTION

Mangrove ecosystems are distributed in coastal waters in tropical and subtropical regions, delivering a range of essential ecosystem services and playing an important role in climate change mitigation [1,2]. They are regarded as overall sinks for atmospheric carbon (C) due to their waterlogged and predominantly anoxic soil conditions and the inhibition of methanogenesis by the inflow and preferred reduction of marine sulphate. Although both nitrification and denitrification can be sources of N_2O emissions from mangroves, net emissions are often limited by the availability of mineral nitrogen (N) as a substrate for chemolithotrophic microbes (nitrification) and an electron acceptor for microbial respiration (denitrification) in most intact mangrove ecosystems [3]. Under natural conditions, the demand for available N to support C capture by mangrove trees is met mainly by mineralisation of soil organic N, biological N fixation and through riverine input of dissolved inorganic N (DIN) into mangroves (**Figure 1**). However, due to the growth of nutrient discharge from anthropogenic sources, such as agricultural intensification coupled with excessive synthetic N fertilizer use worldwide, riverine DIN loads have increased substantially [4], chronically elevating downstream receptor systems, including mangroves (**Figure 1**).

Increased DIN inputs to mangroves in excess of plant metabolic demands pose a significant risk to rising N_2O emission (**Figure 1**), enhancing global warming and stratospheric ozone destruction [5–8]. Given that N_2O is 298 times more potent in inducing global warming than CO_2 in the atmosphere on a mass basis, there is a severe risk that potential benefits of nitrate removal in eutrophied coastal ecosystems such as mangroves can be significantly offset by enhanced N_2O emission.

Unfortunately, global estimates of N_2O emission from mangroves are currently not explicitly included in the annual national greenhouse gas emission budgets and scenario projections of the IPCC [9]. Instead, previous IPCC assessments considered mangroves only under the broader category of global estuaries and riverine systems where emission factors have been developed only for former mangrove ecosystems that have been converted to aquaculture [9]. N_2O emission factors for undisturbed, unconverted, or restored mangrove ecosystems that are similarly exposed to increasing anthropogenic DIN loading have yet to be developed to correctly estimate the real extent of current N_2O emissions from mangroves. Such estimates are needed to accurately assess the implications for future N_2O emissions from mangroves under the scenarios of global increases of DIN inputs into coastal ecosystems [10].

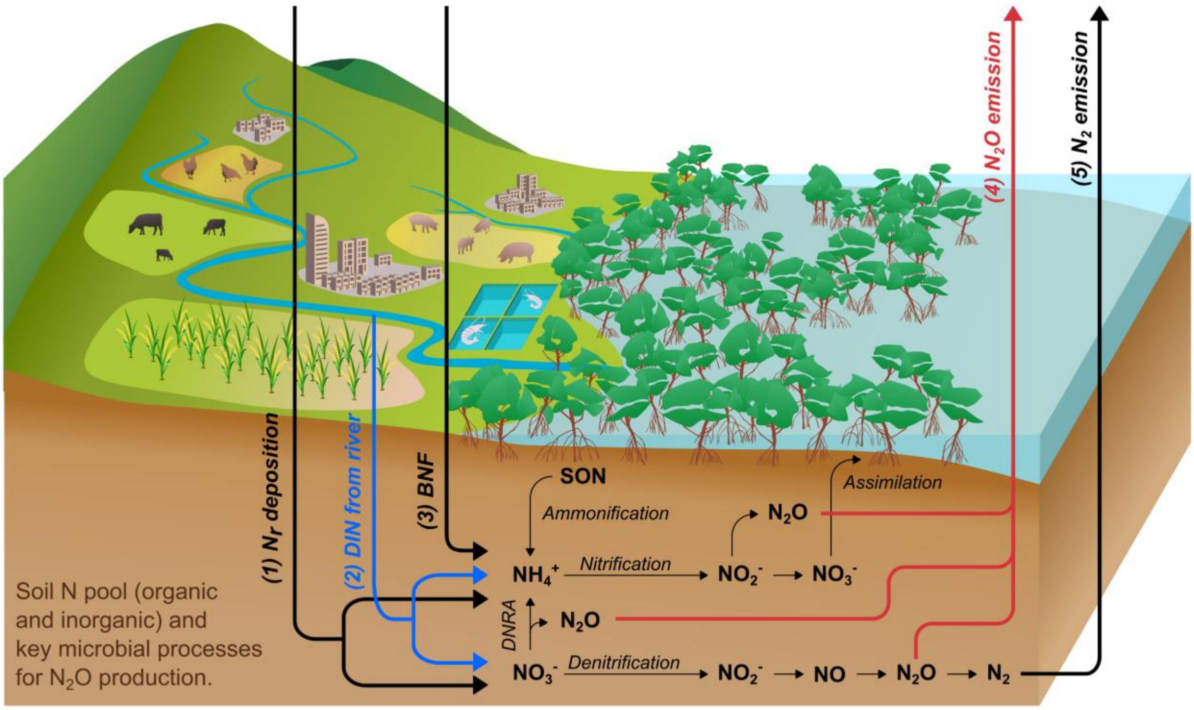

Figure 1. The Nitrogen Cycle in the Mangrove Habitat

Nr: reactive nitrogen; SON: soil organic nitrogen; DIN: dissolved inorganic nitrogen; BNF: biological nitrogen fixation; DNRA: dissimilatory nitrate reduction to ammonium.

The potential oversight of explicit inclusion of current and future N_2O fluxes from mangrove ecosystems suggest that there is an urgent need for development of emission factors for N_2O fluxes under current and projected DIN loading into mangrove ecosystems. Previously estimated values of global mangrove N_2O emissions are highly uncertain [3,6], because they have been upscaled from single-region or median flux values without detailed evaluation of uncertainties. The wide range of estimates is likely caused by regional bias of previous studies and by technological challenges of adequately capturing the inherent spatial variability and temporal dynamics of N_2O emission from mangrove ecosystems. Existing estimates of global mangrove N_2O emissions do not support reliable projections of future increases in anthropogenic riverine DIN inputs and consequent future emissions of N_2O from mangrove ecosystems.

To assess the current extent and future trajectory of global N_2O emission from mangroves under increasing anthropogenic DIN inputs, we performed a systematic global meta-analysis of N_2O emission studies conducted during the past two decades. These studies include 58 site-based mangrove N_2O fluxes of which 26 also contained data on sediment DIN concentration (**Table S1**; **Figure 2A**). We used this information to develop a comparison between mangrove N_2O fluxes and sediment DIN concentrations which were then used in scenarios analyses to estimate future N_2O emission based on the projections of DIN discharge from catchments.

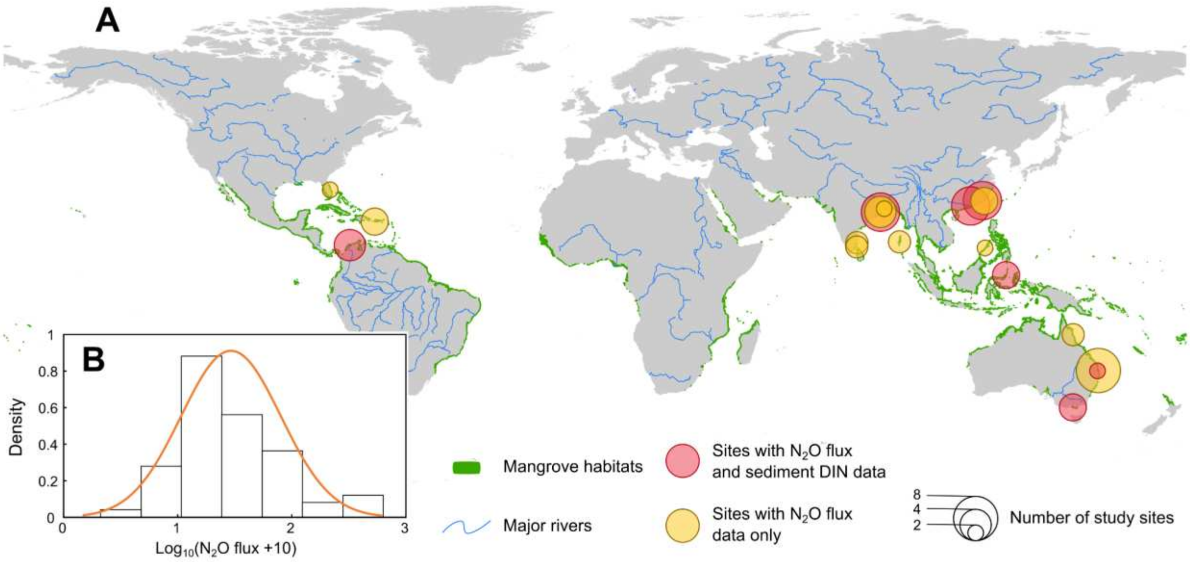

Figure 2. The Distribution of Mangrove Habitats and Mangrove Field Study Sites

(A) Global distribution of mangrove habitats based on Giri et al., [2] and spatial distribution of mangrove field study sites with exclusively N_2O flux data (N = 29) as well as sites with both N_2O flux and sediment DIN concentration data (N = 29). **(B)** Distribution of experimentally observed mangrove N_2O fluxes obtained from 58 field sampling sites globally.

RESULTS AND DISCUSSION

Global N_2O emission from mangroves

We estimate a global mean mangrove N_2O flux of 19.31 μg N m^{-2} hr^{-1} (95% CIs: [12.61, 28.00]) from the 58 site observations that follow a normal distribution passing a Kolmogorov–Smirnov test (**Figure

2B). This average emission rate lies within the range of previously reported N_2O fluxes that vary from 0.42 to 37.50 μg N m^{-2} hr^{-1} [3]. According to a global survey of mangrove ecosystems [2], in the year 2000 mangroves covered a total surface area of 137,760 km^2 in coastal regions north and south of the equator. Based on this surface area, the estimated total global N_2O emission from mangroves for the year 2000 is 0.023 Tg N yr^{-1} (95% CIs: [0.015, 0.034]), which is of similar magnitude as previously reported ranges by Murray et al. [6] with 0.01-0.09 Tg N yr^{-1}, Corredor et al. [5] with 0.009-0.356 Tg N yr^{-1}, and Chauhan et al. [11] with 0.07 Tg N yr^{-1} estimated by upscaling single-region fluxes or median values of several reported ranges. The global warming potential of N_2O emission of 0.023 Tg as N yr^{-1} (0.037 Tg as N_2O yr^{-1}) is equal to an emission of 3.01 Tg as C yr^{-1} given that N_2O is 298 times potent in inducing global warming relative to CO_2 on a mass basis for 100-year time horizon. This is even higher than the mangrove CH_4 emission (2.53 Tg C $year^{-1}$) over 100 years [12].

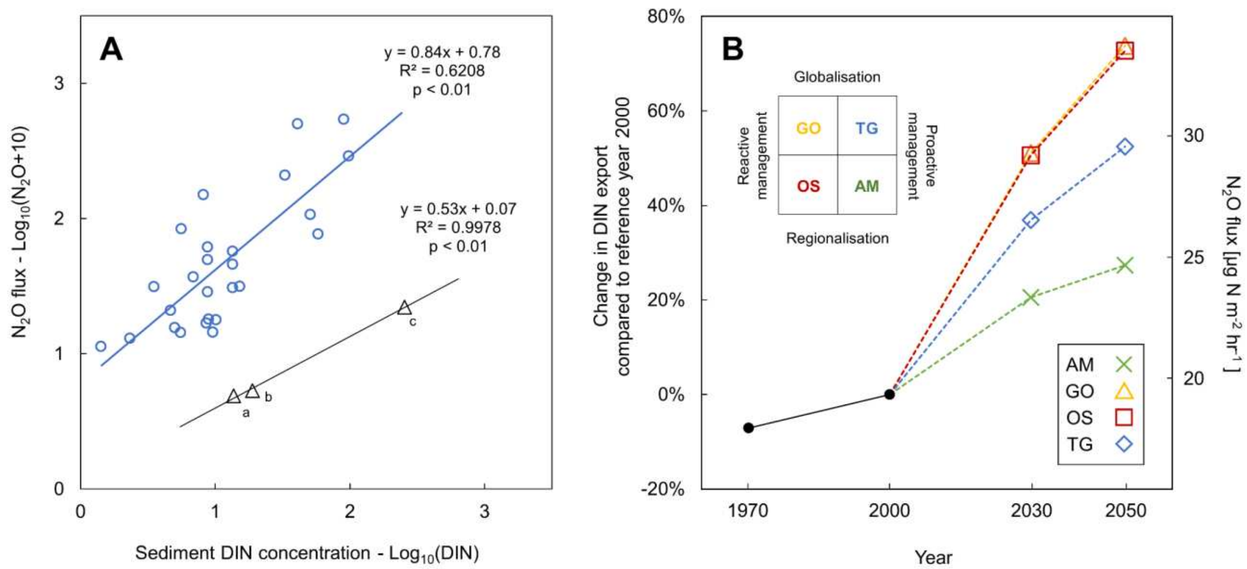

Figure 3. **The Relationship between N_2O Flux and Sediment DIN Concentration and Their Predictions in Future Scenarios**

(A) Log-log plot highlighting the relationship between N_2O flux and sediment DIN concentration. A total of three linear regression models were performed. The first model identified three outliers from the 29 sites, and two additional models were consequently conducted based on the 26 sites and the 3 identified outliers respectively (see Data and Methods). The outcomes of the latter two regression models are presented: the blue solid line denotes the fitted line for 26 points where the 3 outliers (triangles) are excluded; and the black line is the fitted line for the 3 outliers. The three outliers are: a) Likupand, Sulawesi island, Indonesia [34]; b) Teremaal, Sulawesi island, Indonesia [34]; c) Chelmer, Queensland, Australia [40]. **(B)** Trends and future scenarios of the catchment-exported DIN in coastal mangroves and the N_2O flux. The four Millennium Ecosystem Assessment scenarios are: AM – Adapting Mosaic; GO – Global Orchestration; OS – Order from Strength; TG – Techno-garden.

Relationship between N_2O flux and sediment DIN

Our meta-analysis showed a log-log correlation ($R^2 = 0.6208$, $p < 0.01$) between mangrove N_2O flux and sediment DIN concentration observed globally (**Figure 3A**). This indicates that allochthonous nutrient sources from rivers can increase the DIN levels in coastal habitats and sediments [13,14], making substantial contributions to mangrove nitrogen processing and N_2O emission. Using this correlation allows us to estimate future global trajectories of N_2O emission from mangrove ecosystems based on projected anthropogenic DIN fluxes from their respective river basins. Organic matter decomposition in mangrove sediments is slow as compared to catchment imports as evidenced in global reviews of nitrogen dynamics in mangroves [e.g. 3]. Therefore, this correlation compellingly indicates that mangroves are highly efficient users of DIN from riverine source waters, especially in the condition of nitrogen enrichment caused by anthropogenic effluents. The availability of DIN is a key limiting factor for nitrogen transformation rates in the sediment of fringe and interior mangroves, which are generally DIN sinks, taking nitrogen from overlaying waters [6,15,16]. In addition, the autochthonous N input through biological N fixation in mangroves can be suppressed by the high loading of DIN given that BNF is an energy expensive process [17,18]. For example, 10 to 28 g of glucose is invested per gram of N fixed and thus DIN loading will supress fixation [19]. This suggests that N_2O emission in mangroves may increase as a result of anthropogenic N enrichment [3].

Scenarios of future global N_2O emission

We predict how global N_2O emissions from current mangrove ecosystems might rise in the future, based on projections of riverine DIN exports in the four Millennium Ecosystem Assessment scenarios (Adapting Mosaic - AM, Global Orchestration - GO, Order from Strength - OS, Techno-garden - TG) (**Figure 3B**) that consider four different combinations of (i) globalisation vs regionalisation, and (ii) reactive vs proactive approaches to environmental issues [4,20], see Table S3. As a result of such projected increases of riverine DIN exports from their catchments, N_2O emission from mangrove ecosystems will rise by 21-51% in 2030, and by 27-74% in 2050 compared to the emission estimates of year 2000, depending on the respective scenarios (**Figure 3B**).

Thus, these results indicate consistent increases in global N_2O emission from mangrove ecosystems under all of the four scenarios. They contrast with previous studies that show mixed trends of changes in anthropogenic N_2O emissions (from agriculture, energy, transport, biomass burning, etc.) from 2005 to 2050 depending on strategies and scenarios (business-as-usual: 83% increase; moderate mitigation: 26% increase; concerted mitigation: 21% decrease) [21]. Differences in mangrove N_2O emissions among respective scenarios suggests the potential efficacy of various interventions aimed at effectively managing N derived from river catchments. Predicted future N_2O fluxes in the GO and OS scenarios that both follow reactive approaches are similar and among the highest, exceeding predicted future fluxes of the scenarios assuming proactive approaches by 20-21 % (TG) or even 45-46 % (AM) in 2050. The lowest increase in N_2O emissions was predicted for the AM scenario, which has a regional watershed-scale focus and follows strongly proactive environmental management strategies. The recycling of animal manure and human excreta in agriculture in the AM scenario results in decreased DIN exports from catchments towards their coastal mangrove wetlands than the other scenarios that are dependent on the use of synthetic N fertilization of agricultural land uses (**Table S3**).

These results suggest the global significance of a linear increase in N_2O emissions from mangrove ecosystems being triggered by the predicted rising riverine DIN fluxes. The relative proportion of N_2O emitted from mangroves to the total global N_2O emissions (natural and anthropogenic sources) on area (land cover basis) exceeds their earth surface cover by 374.07% (see Supplementary Information), with flux values (19.31 μg N m^{-2} hr^{-1}) that match those from herbaceous wetlands (19.29 μg N m^{-2} hr^{-1}), but greatly exceed that from freshwater forested wetlands (6.05 μg N m^{-2} hr^{-1}), shrubs (6.96 μg N m^{-2} hr^{-1}), grasslands (10.73 μg N m^{-2} hr^{-1}), and other types of forests (boreal: 5.37, temperate: 12.22, tropical dry: 12.56 μg N m^{-2} hr^{-1}) [22]. However, our results indicate that in contrast to other greenhouse gas sinks that turn into sources (e.g. boreal wetlands and melting permafrost), the increase in emissions from mangroves can be efficiently controlled if riverine DIN exports are reduced. A reduction of accumulated N_2O emissions from mangroves as between scenarios GO and AM

(161.20 Tg CO_2 yr^{-1}) is comparable to the global N_2O emissions from the industry (137.91 Tg CO_2 yr^{-1}) and energy (175.86 Tg CO_2 yr^{-1}) sectors in 2010 [23].

Uncertainties in estimation

We contend that our estimates of N_2O fluxes are conservative, being primarily based on surface water flux data using static chambers (**Table S1**). These estimates therefore do not include N_2O transfer from soils through mangrove tree stems and shoots into air under wet and/or inundated conditions, as trees in wetland environments can be significant conduits for transporting greenhouse gases [24–26]. In addition, the majority of the assessed N_2O water-air fluxes are originating from mangrove rivers instead of inundated mangrove habitats (Table S2). Although some pristine rivers are found to act as net sinks of N_2O [e.g. 27,28], mangrove rivers are in general sources of N_2O, especially when they are receiving an increasing load of anthropogenic DIN [3]. However, these water bodies as N_2O sources (see Figure S3) are not necessarily counted in the total estimated area of mangrove ecosystems [2], which may consequently underestimate the total N_2O flux. Lastly, the underestimation may also be caused by the under-represented mangrove habitats in equatorial regions (10°S - 10°N) (see Figure S1), which may have larger N_2O fluxes because of their higher sediment temperature and increased bacterial productivity potentials [6].

Based on the revealed relationship between N_2O fluxes and sediment DIN, the N_2O emissions in future scenarios were predicted using projections of riverine DIN exports. Although external DIN also enters coastal areas via fresh groundwater discharges, their contribution is relatively a small proportion of riverine sources (from 2.4% to 7.5% depending on studies [29–31]) and there is a lack of systematic global projections of DIN input via coastal groundwater discharges to fully demarcate its net contribution to the DIN loading of the mangrove forest sediments. However, given intensified agriculture and population growth posing a risk of increasing DIN discharge via fresh groundwater [29], our projected N_2O emissions are likely to be rather conservative as they do not include the impact of less well constrained groundwater DIN contributions as a predictor. However, global datasets of coastal groundwater discharge have been appearing in recent years [32], making it possible to establish future research if this causes even higher N_2O emissions.

It has been a challenge to obtain a global estimate of the current and future N_2O emission by upscaling local measurements, because of the high spatial and temporal variation of N_2O fluxes and sparse data availability [6,33]. This paper performs a systematic meta-analysis, attempting to overcome the limitations of common extrapolation exercises by upscaling from single-region or median values. The meta-analysis reveals a useful relation between mangrove N_2O flux and sediment DIN concentration, and hence predicts a significant N_2O emission growth in the foreseeable future. However, the estimation of global N_2O flux and emission carries uncertainty (**Figure 3A**). Parts of the uncertainty were caused by the limited data coverage of the high heterogeneity of mangroves and their N_2O emission (e.g. types, locations, seasons, or times of the day) in the existing studies, which potentially obscures the impact of micro-scale hydro-biochemical processes on the relationship. For example, the three outlier sites have much less N_2O fluxes compared to their sediment DIN concentration levels (see **Figure 3A**), which might be caused by their micro-scale ecological attributes such as high salinity that leads to decreased denitrification [34]. Therefore, we suggest that further refinements through experimental work and globally coordinated monitoring with broader coverage are needed to improve the accuracy and robustness of the estimates so that reliable adaptive N and GHG management strategies can be identified.

CONCLUSIONS

Based on a systematic meta-analysis, we estimate the global mean N_2O flux from mangrove ecosystems to be 19.31 μg N m^{-2} hr^{-1}. This number exceeds emissions from freshwater forested wetlands, shrubs, grasslands, as well as boreal, temperate, and tropical dry forests. Considering the global surface area covered by mangroves, N_2O emissions from world-wide mangrove ecosystems are estimated to be 0.023 Tg N yr^{-1}.

Our analyses reveal a significant correlation between sediment DIN and N_2O emission, and a high risk of increased mangrove N_2O emissions by up to 74% in 2050 due to enhanced nutrient inputs from their upstream catchments. Because of their key impact on the global climate, we suggest including global estimates of N_2O emission from mangroves in the annual national greenhouse gas emission budgets and scenario projections of the IPCC. This result also implies that the benefits of mangrove restoration efforts can be optimised if riverine DIN exports are managed efficiently to reduce DIN loading in mangroves, and suggests that this significant biogeochemical connection between rivers and coastal mangrove habitats is needed to be better reflected in a more integrated river basin management approach.

Our study uncovers critical knowledge gaps related to the often site-specific mechanisms that control mangrove N_2O emissions, highlighted by the existence of almost 10% of outliers in the otherwise strong DIN/N_2O relationship found, which suggests that emission rates may be controlled by local or regional factors. We therefore call for globally coordinated mangrove GHG emission monitoring to improve accuracy and robustness of N_2O emission estimates and support mangrove management in the future.

EXPERIMENTAL PROCEDURES

Resource Availability

Lead Contact

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Feng Mao (MaoF1@cardiff.ac.uk).

Materials Availability

This study did not generate new unique materials.

Data and Code Availability

The published article is a systematic meta-analysis and did not generate new datasets. The article includes all datasets analysed during this study.

Mangrove N_2O emission and sediment DIN metadata

Mangrove N_2O flux and sediment DIN concentration data were collected from published literature, based on Web of Science searches using a combination of two topic keywords ‘mangrove’ and ‘nitrous oxide’. We went through all the returned 77 papers and found 2 more papers using the 'snowballing' techniques – these 2 papers were not in the returned searching results but were mentioned or cited by them. 30 out of the 79 papers contain N_2O flux data in mangrove habitats. Within the 30 papers, 26 have flux information at the sediment-air interface, and 6 provide data about N_2O fluxes from surface water. Several of those 26 papers with flux information also provide nitrogen concentration data in different forms (e.g. NH_4-N, NO_3-N and total nitrogen) and locations (e.g. in sediment, porewater and surrounding surface waters). Among these, the sediment dissolved inorganic nitrogen (DIN) information can be obtained directly or by combining NH_4-N, NO_3-N and NO_2-N concentration in 16 of all papers, making DIN the most common and comparable nitrogen concentration variable. The DIN concentration data from 29 sites of 12 scientific publications are provided in 'mass per mass' units (e.g. μg N g^{-1}) while the data from 4 sites in 4 papers are provided in 'mass per volume' units (e.g. μM). These two unit-systems are not directly comparable, so that the first 29 sites were used for analysing the relationship between N_2O flux and sediment DIN concentration.

Within each paper, the N_2O flux for a sampling site may be measured in different replicates, locations (e.g. distance to the coast), seasons, or times of the day. These measurements were combined to estimate a mean N_2O flux for each sampling site in a standardised unit (μg N m^{-2} hr^{-1}).

Not all published flux and concentration data were provided explicitly in text or tables. For the those presented in bar-charts, the length of bars was measured and converted into standard data formats using ImageJ (version 1.51j8).

Two sets of data were consequently formed (**Figure 2A**): the first set has 58 sites from 26 scientific publications, each with data of N_2O flux at the sediment-air interface; the second set is comprised of 29 sites from 12 publications with both the data of N_2O flux at the sediment-air interface and the data of DIN concentration in sediment (see **Table S1**).

Global mangrove distribution

According to the map produced by Giri et al. [2], mangroves had a global total area of 137,760 km^2 in the year 2000. The World Atlas of Mangroves [35] also has an estimation of the total mangrove area of

152,361 km^2. Spalding's study uses a range of different image-processing techniques but has considerable expert validation while Giri's work provides a high-resolution dataset using consistent and repeatable methods although with less expert review [36]. We used Giri's map in this research and the data was downloaded from the UNEP-WCMC's ocean data viewer (http://data.unep-wcmc.org/datasets/4).

Estimation of mangrove N_2O flux

The global mean mangrove N_2O flux was estimated based on the 58 sites from 26 papers that provide flux data (**Table S1**).

The flux was logarithmised as:

$$E_{log} = \log_{10}(E + 10)$$

where E denotes the original mangrove N_2O flux value (μg N m^{-2} hr^{-1}), and E_{log} denotes the logarithmised value. A 10 was added onto E since some of the original values were below zero.

The normality of the logarithmised sample distribution was tested using the Kolmogorov-Smirnov normality test in R [37]. The mean and standard deviation of the normally distributed sample was calculated by the maximum likelihood fitting using the 'fitdistrplus' package in R [38].

Relationship between N_2O flux and sediment DIN

The sediment DIN was logarithmised as:

$$DIN_{log} = log_{10}(DIN)$$

where DIN denotes the original sediment DIN value (μg N g^{-1}), and DIN_{log} denotes the logarithmised value.

The linear regression model was used to find the relationship between the N_2O flux and the sediment DIN concentration.

$$E_{log} = \alpha + \beta DIN_{log} + \epsilon$$

Linear regression was performed three times using slightly different datasets.

The first model was built based on 29 sites from 12 papers that provide both flux and sediment DIN information (**Table S1**). Based on the result of the first model, 3 outlier sites were removed from the 29 sites because they are isolated from the general trend of the data pattern, deviate significantly from the y = x line of the diagnostic normal Q-Q plot with extreme standardised residuals (**Figure S2**). The rest 26 sites from 10 papers were imported to build the second model, and the 3 outlier sites were used to build the third model (**Figure 3**).

DIN discharge from catchments

The Nutrient Export from WaterSheds 2 (NEWS2) is an integrated model of nutrient exports from more than 6000 rivers worldwide [39]. Using this model, Seitzinger et al. [4] estimate and analyse the past trends and future trajectories of river DIN export in four Millennium Ecosystem Assessment scenarios, namely Adapting Mosaic (AM), Global Orchestration (GO), Order from Strength (OS) and Technogarden (TG) (**Table S3**). The model output that is the data of river DIN export from each river were requested from the authors, covering the following years and scenarios: 1970, 2000, 2030-AM, 2030-GO, 2030-OS, 2030-TG, 2050-AM, 2050-GO, 2050-OS, 2050-TG. The changes in DIN export are provided in **Figure S4** and **Figure S5**.

Trend of mangrove N_2O emission

The past and future trajectories of N_2O emission were estimated using two sets of information. First, the calculated relationship between N_2O flux and sediment DIN concentration described above. Second, the historical and predicted future DIN export from river basins that have river mouths neighbouring coastal mangroves. For each mangrove habitat, the closest river basin was identified according to the distance between the habitat and the river mouths using ArcMap 10.4.1. The DIN export from the closest basin was regarded as the main influencer of the sediment DIN in the adjacent mangrove habitat. The uncertainty of the prediction is presented in the form of scenario analysis, and the 95% CIs of estimated N_2O flux and emission for each predicted year-scenario are provided in

Table S4. The total area of mangrove habitat (137,760 km^2) is assumed to remain the same as in all years and scenarios [2], avoiding introducing additional uncertainties in predicting the distribution change of mangrove under the joint influence of both forest degradation and restoration efforts.

Comparison between mangroves' proportional global N_2O emissions and proportional earth surface coverage

According to Ciais et al. [10], the total global N_2O emission is 17.9 Tg N yr^{-1}, including 11.0 Tg N yr^{-1} from natural sources and 6.9 Tg N yr^{-1} from anthropogenic sources. Our estimated mangrove N_2O emission in this paper is 0.023 Tg N yr^{-1}. The mangrove's proportion on global N_2O emission is 0.023/17.9 = 0.128%. The total area of mangroves is 137,760 km^2 [2] while the total earth surface area is 510,072,000 km^2. The mangrove's proportion on earth surface is 137,760/510,072,000 = 0.027%. Therefore, the mangrove's proportion on global N_2O emission exceeds their proportion on earth surface cover by: (0.128-0.027)/ 0.027 = 374.07%.

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AUTHOR CONTRIBUTIONS

Conceptualization, Methodology, and Writing – Original Draft, F.M., S.K., and S.U.; Formal analysis and Visualisation, F.M.; Writing – Review and Editing, F.M., S.K., S.U., D.M.H., and S.M.G.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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