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Challenges for Global Sustainable Nitrogen Management in Agricultural Systems

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ABSTRACT: Nitrogen (N) losses from agricultural production contribute to detrimental impacts on water, soil, air, and human health. However, it is still lacking in evaluating global N budgets in agricultural systems. Hence, we conducted a global analysis on the current status of the N flows in the agricultural systems, explored the possible mitigation measures and challenges, and investigated the existing regulations on controlling N pollution. Globally, agricultural soils received a total of 73 kg of N ha^{-1} $year^{-1}$ on average, including N fertilizer plus manure (61%), atmospheric N deposition (10%), and N litters and fixation (29%). The estimated global NH_3 loss to total N inputs was 17%, which led to a loss of \$15 billion $year^{-1}$. The N use efficiency (NUE) in Eastern China (33%) was much lower than that in the Eastern United States (65%) or Western Europe (61%), leaving much room to enhance the NUE to increase agricultural food production. Meanwhile, higher NH_3 losses from N fertilizers and manure were found in Eastern China (22%) than the Eastern United States (17%) and Western Europe (17%). We highlight the urgency to improve the NUE and decrease NH_3 loss with lower environmental consequences. Our results showed high potentials to mitigate NH_3 volatilization and enhance the NUE by various measures, such as substituting manure N for chemical fertilizer N, applying controlled release fertilizers, and urease inhibitors. These measures should be implemented in combination with the transfer of knowledge to farmers with new technologies and increasing the farm size to enhance the efficiency of agricultural production in the future.

KEYWORDS: *nitrogen budgets, NH_3 losses, nitrogen use efficiency, agricultural systems, sustainable agriculture*

■ INTRODUCTION

Over the past 50 years, the global nitrogen (N) cycle has undergone tremendous changes,[1] closely related to the extraordinary increase of agricultural synthetic N fertilizer.[2] Chemical N fertilizer and manure are often used exceeding crop requirements, causing high ammonia (NH_3) volatilization, loss of nitrous oxide, nitrate leaching, and runoff.[3] NH_3, as a precursor of fine particulate matter formation, can lead to air quality degradation and then damage human health.[4] Moreover, excessive atmospheric deposition of ammonium (NH_4^+) and NH_3 can also degrade sensitive terrestrial and aquatic ecosystems.[5] This associated NH_3 pollution has become a problem for environmental agencies, scientists, and agricultural policy makers around the world.

Regulation of NH_3 in agricultural systems is needed urgently toward sustainable agricultural production, human health, and environmental benefits.[6] Before controlling agricultural N loss, understanding N cycle and sources is necessary from both chemical and biological perspectives.[5] These are linked by many factors, such as climate and field variability, soil characteristics, management practices, cropping systems, and geographical areas.[7] Any regulation for reducing N loss in the agricultural systems should take into account management practices with consideration of all aspects of the N cycle.[8] Nitrogen use efficiency (NUE) is an essential indicator in the assessment of the performance of fertilizer application in agricultural systems.[9] Quantifying the current status of NUE is crucial to enhance N management and decrease detrimental environmental consequences.[7] Several previous studies have analyzed and quantified the N flows in the fields with N fertilizer application at local scales, the NUE, and the amounts of NH_3 loss.[7,10,11] However, the field measurements of N flows (such as NH_3 volatilization and the NUE) are still scarce around the globe as a result of the high cost, expertise, and labor.[10]

Instead, the process-based models can supply an effective alternative way to study the N budgets in agricultural systems and simulate biogeochemical processes in the soil.[8,12,13] The denitrification decomposition (DNDC) model can be applied to stimulate N flows in agricultural systems and finely validated by numerous ground-based measurements.[8,14−17] Previous works have investigated the impacts of agricultural management on N flows at local scales, but very little work quantified comprehensively the management practices and explored mitigation strategies for NH_3 loss on a global perspective. In

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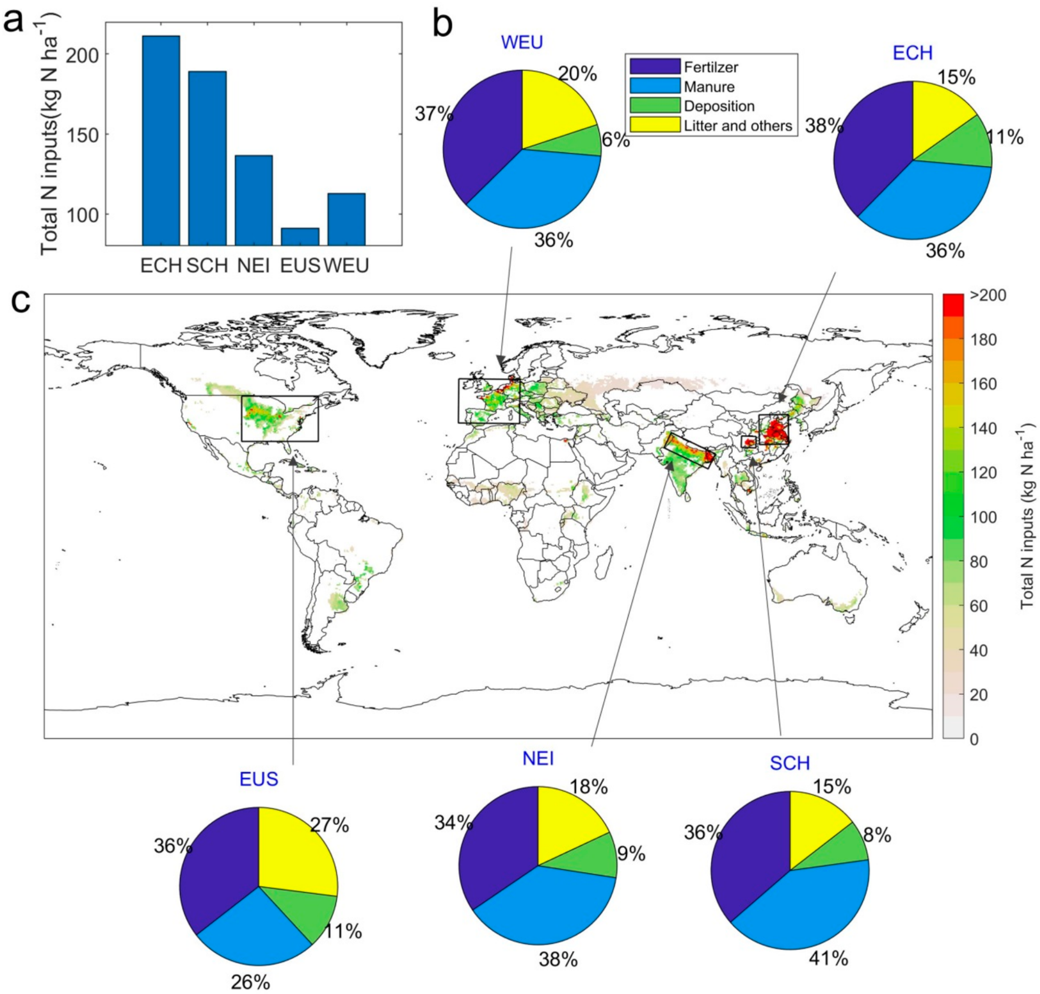

Figure 1. Total N inputs in cropping systems, including manure amendment, synthetic N fertilizer, atmospheric N deposition, litter (crop residues), and others. (a) Summary of total N inputs in hotspot areas of WEU, EUS, NEI, SCH, and ECH. (b) Each contributor to total N inputs in the hotspot regions. (c) Spatial distribution of total N inputs. The global map of political boundary data was available from https://map.igismap.com/share-map/export-layer/TM_WORLD_BORDERS-0.3/502e4a16930e414107ee22b6198c578f, created by OpenStreetMap contributors and licensed under a CC BY-SA license (https://creativecommons.org/licenses/by-sa/2.0/).

this study, we systematically evaluated N flows in cropping systems, the contribution of NH_3 loss to total N inputs, and the NUE in hotspot regions, at the global scale. Previous studies also show management measures are essential for mitigating N loss in the agricultural system, such as improving fertilizer efficiency (applying urease inhibitors, controlled release fertilizers, substitution of manure for chemical N fertilizer, etc.) and implementing scientific farmland management (irrigation immediately, deep placement of N fertilizers, crop residue retention, etc.).[18−20] Thus, we also demonstrated our insight into current challenges for sustainable N management in global agricultural systems and provide possible pathways to mitigate NH_3 losses.

■ METHODS

Data Sources. To identify the spatial distribution of global croplands, we used the Global Mosaics of MODIS land-use (MCD12Q1), which is generated by integrated supervised classification algorithms.[21] Meteorological data included total precipitation, maximum temperature, and minimum temperature at a daily time step from Climate Prediction Center (CPC) global unified data at a resolution of 0.5° grids (https://www.esrl.noaa.gov/psd/). The N fertilizer and manure data were obtained from the Data Center in NASA's Earth Observing System Data and Information System[22] (http://sedac.ciesin.columbia.edu). The crop-specific N fertilizer was gained from Mueller et al.,[23] and the data set of crop-specific N fertilizer can be gained at http://www.earthstat.org/. N deposition data sets were obtained from GEOS-Chem by Geddes et al.[24] The soil parameter data of pH, soil organic matter (SOM) fraction, clay fractions, and bulk density were obtained from the Soil Database of China for Land Surface modeling (http://globalchange.bnu.edu.cn). Data on the management, residues, tillage, and cropping systems were adopted by Global Landscapes Initiative (http://www.earthstat.org/), Beach et al.,[25] Smith et al.,[13] and Yu et al.[26] The long-term NH_3 volatilization data during 1970−2010 were gained from EDGAR (version 4.3) (https://edgar.jrc.ec.europa.eu/htap.php#), and the trends of NH_3 during 2010−2016 were obtained from satellite data of infrared atmospheric sounding interferometer (IASI) retrievals (http://cds-espri.ipsl.upmc.fr/).

Biogeochemical Modeling of Cropland N Flows by DNDC. DNDC is a N-oriented model, which can be used to simulate crop growth and the biogeochemical processes of decomposition by microbial activities, denitrification, and nitrification in agricultural systems.[3] It contains a mass balance methodology for C, N, and water in air, plants, and soil.[14] The impact of N on cropping systems is closely associated with human management practices, soil properties, and climate.[15] We used the DNDC to simulate the N budgets, the NUE, and NH_3 volatilization globally. The baseline scenario was set

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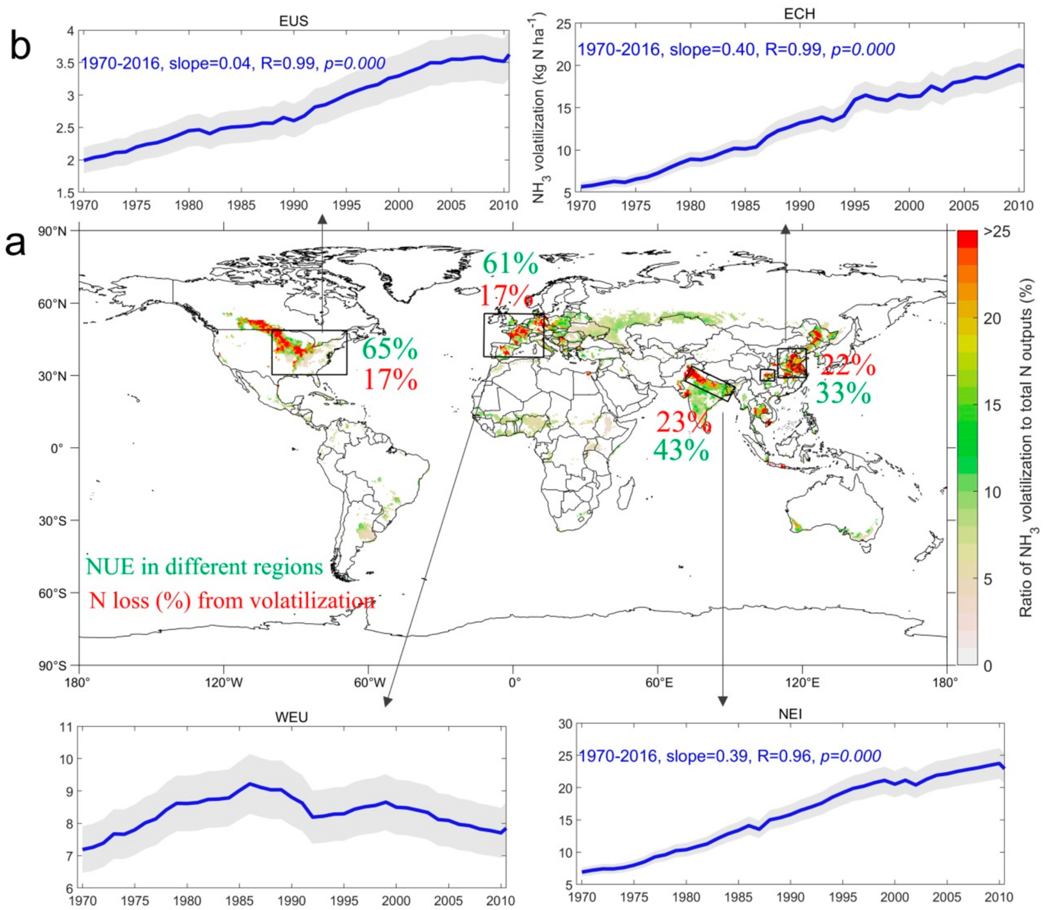

Figure 2. Ratio of NH_3 volatilization to total N inputs and the NUE in different regions. (a) Spatial distribution of NH_3 volatilization to total N inputs. (b) Annual changes of NH_3 volatilization in hotspot regions during 1970−2010. The global map of political boundaries data was available from https://map.igismap.com/share-map/export-layer/TM_WORLD_BORDERS-0.3/502e4a16930e414107ee22b6198c578f, created by Open-StreetMap contributors and licensed under a CC BY-SA license (https://creativecommons.org/licenses/by-sa/2.0/).

using the 2010 conditions for fertilization (chemical N and manure), crop parameters, soil, irrigation, and land use. NH_3 volatilization was quantified on the basis of soil NH_4^+, aqueous NH_3, pH, texture, temperature, and wind speed under different agricultural management practices.[14,27] We used DNDC to assess the impact of management measures on NH_3 volatilization from cropping production systems, which is a well-tested biogeochemical model supporting multipurpose analyses compared to other approaches (http://www.globaldndc.net).[28,29]

The N budget can be derived by quantifying the soil N inputs and outputs.[30]

$$\text{DepN} + \text{FerN} + \text{ManN} + \text{litterN} + \text{FixN} = N_2O + NO + N_2 + NH_3 + \text{cropN} + \text{leachN} + \text{runoff} + \text{dson} + \text{dsin} \quad (1)$$

Inputs of N include atmospheric deposition (DepN), chemical fertilizer N (FerN), manure N (ManN), litter N from residues of crops (litterN), and biological fixation (FixN). Outputs of N include crop uptake (cropN), NH_3 volatilization, N runoff and leaching (leachN), gaseous N_2O, NO, N_2, and soil dissolved organic and inorganic N (dson and dsin).

Daily NH_3 volatilization is calculated as[14,28,29]

$$F_{NH_3} = NH_3(\text{l}) \times \text{ddf} \quad (2)$$

where ddf is the volatilization coefficient, F_{NH_3} is the NH_3 volatilization, and NH_3(l) is the NH_3 concentration in soil water.

Dubache et al.[20] found that the ddf was impacted by wind speed, soil temperature, soil depth, vegetation canopy, clay content, soil moisture, and rain-induced canopy wetting. In this study, we revised the DNDC95 code according to Dubache et al.[20] using following equations:

$$\text{ddf} = f_{\text{wind}} f_{\text{temp}} f_{\text{depth}} f_{\text{canopy}} f_{\text{clay}} f_{\text{water}} f_{\text{rain}} \quad (3)$$

$$\begin{cases} f_{\text{wind}} = 0.1 + 1.5S_{\text{wind}}/(1 + S_{\text{wind}}) \\ f_{\text{canopy}} = 0.4e^{-0.15\text{lai}} + 0.6 \\ f_{\text{depth}} = (q - j)/q \\ f_{\text{clay}} = 0.4e^{-0.1\text{clay}} + 0.6 \\ f_{\text{temp}} = 0.1 + 2.0T_{\text{soil}}/(45 + T_{\text{soil}}) \\ f_{\text{water}} = 0.45e^{-10\text{WFPS}} + 0.55 \\ f_{\text{rain}} = 0.65e^{-1.0\text{lai}\times P} + 0.35 \end{cases} \quad (4)$$

where S_{wind} is the wind speed, lai indicates the leaf area index, q represents the total soil layer number, clay is the soil clay content, T_{soil} is the soil temperature, WFPS is the air-filled porosity, and P is the daily precipitation.

The NUE is a widely used indicator evaluating the efficiency of N inputs (biological N fixation, deposition, manure and fertilizers, and litter N) harvested in biomass, calculated as[6]

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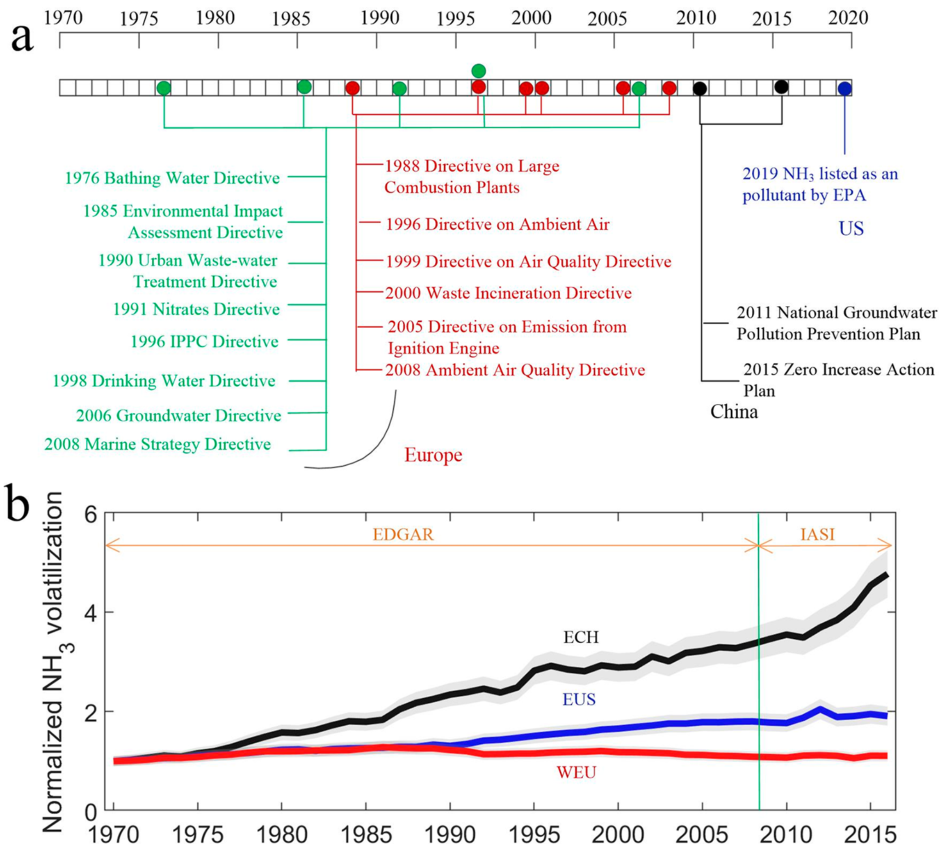

Figure 3. Amendments to control N pollution and normalized NH_3 volatilization during 1970−2016. (a) N-related pollution control regulations. (b) Temporal changes of NH_3 volatilization, normalized to the 1970 level. The trend of NH_3 during 2008−2016 was derived from the trend of IASI NH_3 retrievals.

$$NUE = \frac{cropN}{totalN} \times 100 \tag{5}$$

where cropN indicates N output harvested by crops and totalN represents all N outputs included in eq 1.

Uncertainty Analysis. The driven factors influencing the modeling of N flows are related to the meteorological data, N fertilizer, N manure, N deposition, and soil properties (pH, texture, SOM, bulk density, etc.). We used the minimum and maximum soil properties, temperature, precipitation, and set fluctuations of N fertilizer, N manure, and N deposition within ±20% to assess the possible range of modeling results. All of the results presented in the figures were the mean values, and the annual fluctuations were within ±18% of simulated global cropland N flows. These uncertainties are systematic rather than random and should not affect conclusions of regional comparisons and spatial gradients of N budgets.

■ RESULTS

Overview of Total N Inputs in Cropping Systems. Globally, cropland soils received a total of 73 kg of N ha^{-1} $year^{-1}$ on average in 2010 (Figure 1), including N fertilizer plus manure (61%), atmospheric N deposition (10%), and N litters and fixation (29%). This is consistent with the traditional perspective that a cropland soil is predominately impacted by N fertilizer plus manure, which are common practices in cropping systems around the world.[1] Currently, N manure is an important fertilizer type in cropping systems, 55% of total N fertilizer on average in the global croplands. N litters (from crop residuals) also comprise 29% of N input, highly linked with the activity of the soil microbes mineralizing organic N to NH_4^+.[16,31] With the rapid reactive N emissions, atmospheric N deposition also contributes to 10% of total N inputs. In particular, hotspots of total N inputs were identified globally, including Western Europe (WEU), Eastern United States (EUS), Northeastern India (NEI), Sichuan Basin (SCH), and Eastern China (ECH), as the major areas with intensive agricultural production. The ECH region was the most contaminated N area (221 kg of N ha^{-1}), approximately triple the global average (73), followed by SCH (189), NEI (136), WEU (113), and EUS (91).

Current Status of NUE and NH_3 Volatilization. The NUE is an important efficiency index to evaluate the progress toward achieving sustainable agricultural production.[6,10] The major reason for low NUE is the N loss from the cropland system through NH_3 volatilization, gaseous NO, N_2O, and N_2 emissions, runoff, and leaching.[3] Generally, NH_3 volatilization is the main mechanism of many agricultural production systems, as a global problem requiring to be solved.[11] Estimated global NH_3 loss percentage was 16.96% in this study, which is close to the estimate (17.60%) by Pan et al.[11] and slightly higher than the estimate (10−14%) from the Intergovernmental Panel on Climate Change (IPCC) reports.[11] The global average ratio of NH_3 volatilization to total N inputs (16.96%) is equal to a loss of \$15 billion, with the demand for 112 million tons of N [from the Food and Agriculture Organization of the United Nations (FAO)] (~\$350/ton of urea).[11] With regard to the hotspot regions of N inputs, the NUE in the ECH was 33% (Figure 2), which was close to the estimate (36−39%) by Gu et al.[6] China's NUE was much lower than that in the EUS (65%) and WEU (61%), leaving much room to enhance the NUE to increase

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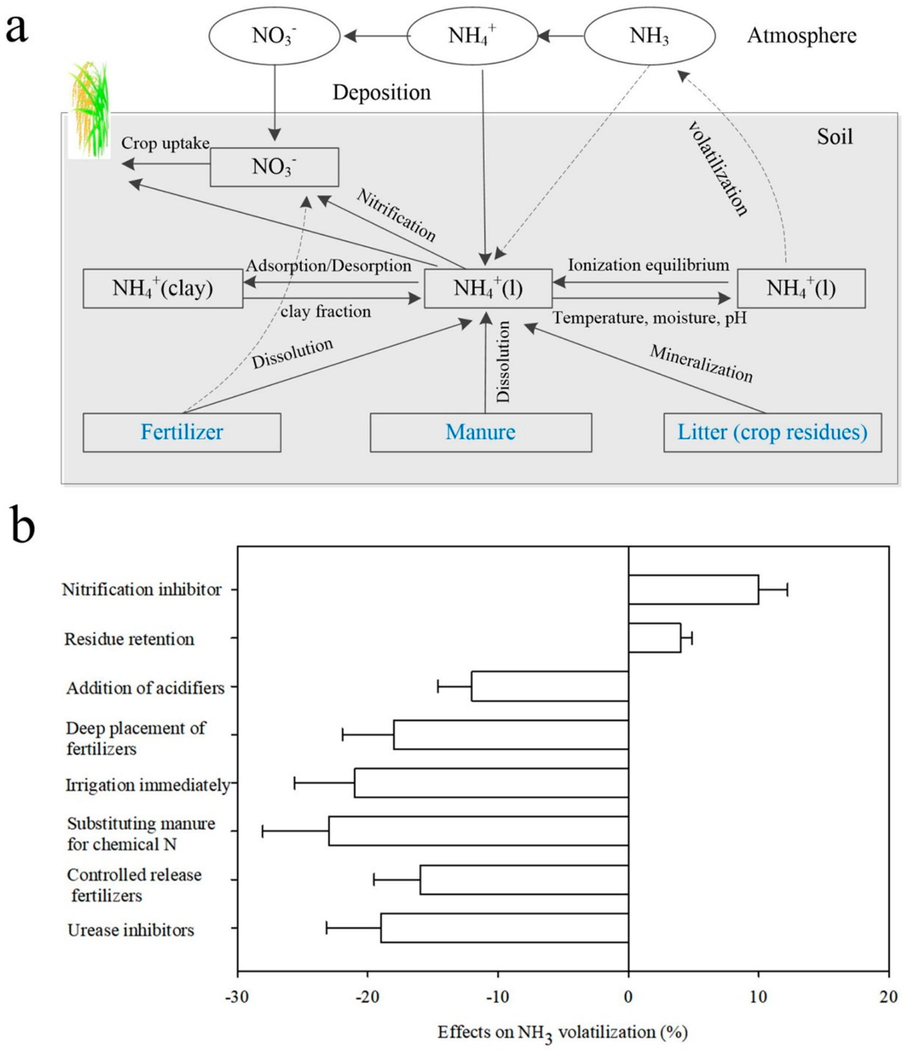

Figure 4. Schematic of the NH_3-related process. (a) Processes of soil NH_4^+ and NH_3 concentrations in the cropping system. (b) Potential measures for NH_3 mitigation.

agricultural food production in China, with only 7% of the global croplands feeding 20% of the global population. Correspondingly, higher NH_3 losses from N fertilizers and manure were found in the ECH (22%) than the EUS (17%) and WEU (17%). The ECH region has been the largest hotspot of NH_3 volatilization globally, resulting from the highest N inputs to croplands and the low NUE. On the basis of the EDGAR estimates, NH_3 volatilization has increased rapidly during 1970−2010 for ECH (0.4 kg of N ha^{-1} $year^{-1}$), EUS (0.04 kg of N ha^{-1} $year^{-1}$), and NEI (0.39 kg of N ha^{-1} $year^{-1}$), except for WEU with a continuous increase before 1986 (0.10 kg of N ha^{-1} $year^{-1}$) but a substantial decrease (−0.04 kg of N ha^{-1} $year^{-1}$) since then.

Existing Regulations for Controlling N Pollution. The European Union (EU) Common Agricultural Policy (CAP) was signed in 1958 contributing to the agricultural modernization and experienced several reforms together with a series of water and air quality control regulations (Figure 3a), significantly influencing the NUE and NH_3 loss in the WEU. However, there were very limited regulations for NH_3 in China and the U.S., causing a continuous increase in NH_3 volatilization since 1970 (Figure 3b). With increasing evidence to support the important contribution of NH_3 to fine particulate matter pollution,[32,33] in 2019, the United States Environmental Protection Agency (U.S. EPA) has listed NH_3 as a pollutant, supported by the report from the U.S. EPA's Integrated N Panel to the Science Advisory Board. In 2015, China's Ministry of Agriculture formally embarked on the "zero increase action plan (ZIAP)", requiring less than 1% annual increase in N fertilizer use during 2015−2019 and no further increase since 2020.[6] However, according to the satellite retrievals, NH_3 columns increased continuously after 2015 (Figure 3b), which may be associated with NH_3 loss from organic N manure in livestock production because ZIAP only controlled the N fertilizer amounts.

Measures for Enhancing the NUE and Reducing NH_3 Volatilization. NH_3 volatilization decreases the N available for plants and leads to a series of environmental consequences. Therefore, there is an urgent need to systematically analyze the effect of mitigation strategies toward reducing NH_3 volatilization in crop systems (Figure 4).

First, improving fertilizer efficiency has been widely recognized to enhance the NUE and minimize NH_3 volatilization from cropping systems.[5,6] Applying urease inhibitors slowing urea hydrolysis[9] could substantially reduce NH_3 volatilization by 24, 16, and 17% in ECH, the U.S., and

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Europe (averaged by 18%), respectively. Controlled release fertilizers extending the availability of N for crop uptake and minimizing urea hydrolysis could substantially decrease NH_3 volatilization by 19, 14, and 15% in ECH, the U.S., and Europe (averaged by 16%), respectively. Substituting 20% chemical N (urea) with equivalent manure can substantially reduce NH_3 volatilization (21%), which could improve the NUE by 15, 25, and 22% in ECH, EUS, and WEU, respectively. Substituting manure for chemical N could enhance immobilized N by microbes and improve the capacity of soil to hold water, microbial activities, and soil structure.[9] Second, implementing scientific farmland management was another crucial strategy toward improving the NUE and reducing NH_3 volatilization. Irrigation immediately following N fertilizer application by washing N into the deep soil to be adsorbed can enhance the NUE by 14, 14, and 17% in ECH, EUS, and WEU, respectively, and can reduce NH_3 volatilization by 20% on average. Specifically, irrigation immediately contributes to urea hydrolysis, allows NH_4^+ to be adsorbed by plants, and therefore increases the NUE and decreases the conversion of NH_4^+ to NH_3 volatilization.[11,34,35] In addition, deep N fertilizer placement and addition of acidifiers could also decrease NH_3 volatilization significantly by 17 and 11%. Notably, crop residue retention increased NH_3 volatilization as a result of restricted movement of N fertilizer into the deep soil;[11] nitrification inhibitors applied for mitigating N_2O emission can unexpectedly increase NH_3 volatilization (∼10%).

DISCUSSION

Research on agricultural NH_3 volatilization and the NUE at the local scales has been undertaken separately in recent years[5,6,11] but lacking a global perspective on the current status of total N budgets, the possible mitigation measures and challenges, and the existing regulations on controlling N pollution. Building on these issues, we present the status of the N budgets in the cropping systems and highlight the urgency to improve the NUE and decrease NH_3 loss to reduce the environmental consequences. Agricultural N fertilizer and manure have a substantial impact on environmental quality, given the low NUE and high NH_3 loss globally. Currently, the NUE ranged from 31 to 65% in the selected hotspots with intensive N inputs. In particular, China's NUE (31%) is much lower than that of the U.S. (65%) and Europe (61%), while NH_3 volatilization in China is triple that in the U.S. and Europe. Moreover, a continuous increase in NH_3 volatilization since 1970 occurred in China and the U.S. as a result of the lack of effective regulations. The increase rate of NH_3 volatilization in China is 10 times greater than that in the U.S. since 1970. Our results show that a great potential exists to mitigate NH_3 volatilization and improve the NUE by various strategies, for instance, substituting manure for chemical N and applying controlled release fertilizers and urease inhibitors. However, these identified measures, such as substituting manure for chemical N, certainly need additional expenditure from farmers, and therefore, a fertilizer subsidy policy should also be carried out on agricultural systems to match these measures.

The total N input in ECH's croplands is more double than that in the EUS and WEU. The reason that Chinese farmers apply so much more N chemicals than the other regions may be closely linked with the small farm size (∼0.1 ha on average for each parcel of cropland) in China.[36] It is difficult to persuade farmers to limit their input of chemical fertilizers because many people still believe higher crop yields can be achieved through more chemical fertilizers.[10] Moreover, in such a small scale, it is difficult to transfer knowledge of modern management practice (such as 4R nutrient stewardship) to farmers and apply technological innovations (such as increasing feed conversion ratio in the livestock subsystem), with the high financial cost.[10] In the future, transfer of knowledge to farmers with new technologies should be conducted toward better agricultural managements, together with increasing the farm size to enhance the efficiency of agricultural production.

In contrast, the WEU is the only region having a continuous decrease in NH_3 volatilization since the late 1990s, with numerous mature regulations on N pollutions. N flows in Europe are regulated by various policy measures, such as input control (agricultural application restriction), emission control (manure application and storage), N concentration restriction in air and water, N exposure restriction, and critical N load.[37] China and the U.S. need to learn from the WEU regarding the NH_3 emission control framework and measures toward achieving sustainable agricultural production. Previously, the effects of NH_3 on air quality and human health were debated heavily for the limit targets to be achieved in China and the U.S. Fortunately, the U.S. EPA has listed NH_3 as a pollutant in 2019 as a result of its critical contribution to fine particular matter,[38] under the background that the acidic gases (SO_2 and SO_2) have decreased in a recent decade.[39,40] Also, China has started ZIAP for controlling the amounts of N fertilizer in 2015. Now, it is time to manage agricultural N to reduce the N-related environmental consequences globally, toward a more sustainable outcome. Non-chemical or organic farming established on the basis of biological principles may have the prospect for addressing the N loss pollution of chemical farming.[41] It depends upon various biological processes to maintain soil fertility, meet crop nutrition, and establish a biological system to prevent weeds and pests.[41−43]

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Notes

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