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Water Scarcity Risks in Ammonia Fertilizer Production Pose a Threat to Global Food Security

Lorenzo Rosa,* Andrea Citrini, Tom Terlouw, and Stefano Mingolla

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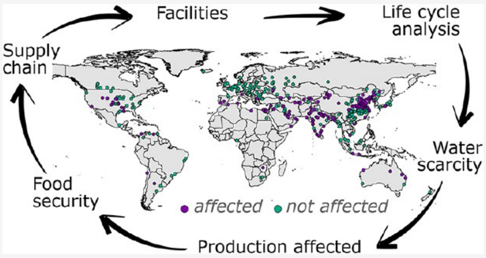

ABSTRACT: Ammonia, the foundation of fertilizers, grows food that feed 3.8 billion people. While recent efforts focus on ammonia emissions and costs, water use and scarcity risks remain understudied. We quantify water consumption of ammonia production, evaluate exposure to water scarcity for each of the 406 global plants, and trace how fertilizer trade redistributes water stress across supply chains, estimating how many people rely on food grown with fertilizers produced in water-scarce regions. We find that ∼18% of global ammonia output (∼33 Mt NH_3 yr^{-1}) experiences at least one month of scarcity annually. The sector's reliance on 406 large, geographically concentrated plants further heightens vulnerability, as local shortages can cascade globally through highly interconnected trade networks. Five exporters (China, Russia, Egypt, Saudi Arabia, and Qatar) account for half of global fertilizer exports, linking the food security of 637 million people to production under water-stressed conditions. Major importers such as Brazil, the U.S., and India are indirectly exposed to water scarcity in distant basins, with the largest trade routes including Qatar−U.S., Qatar−Brazil, and China−Brazil. We show that water scarcity at ammonia production sites represents not merely a local constraint but a systemic risk to global food systems, highlighting the importance of explicitly incorporating water availability into decarbonization strategies and trade policies.

KEYWORDS: *Fertilizers, Ammonia, Life Cycle Analysis, Resilient Agricultural Supply Chains, Water Scarcity, Virtual Water Trade*

■ INTRODUCTION

Agricultural productivity, and the ability to feed the global population, depends on fertilizers that provide essential nutrients like nitrogen, phosphorus, and potassium.[1] Nitrogen is the most consumed nutrient in agriculture, with its supply derived from either manure (33%) or industrially synthesized ammonia (67%).[2] Ammonia is the key industrial form of nitrogen fertilizer, serving as the building block for urea, ammonium nitrate, and other nitrogen-based fertilizers.[3] Ammonia-based fertilizers are fundamental for modern agriculture, supporting the growth of crops that feed approximately 3.8 billion people.[1,3] As the demand for food continues to rise,[4] the use of nitrogen fertilizers is also increasing.[5] Today, ammonia production is geographically concentrated, with only 61 countries hosting the world's 406 ammonia production facilities, leaving many nations, especially in the Global South, heavily dependent on fertilizer imports.[3]

In 2021, 99% of industrial ammonia synthesis was powered by fossil fuels through the Haber−Bosch process.[6] Ammonia production is both highly energy- and carbon-intensive, accounting for 1% of global greenhouse gas emissions (≈450−500 Mt CO_2e annually).[7] Yet it is not only ammonia production that contributes to greenhouse gas emissions, but also its use.[5] Fertilizer application adds ∼660 Mt CO_2e annually, mainly due to nitrous oxide (N_2O), which is a greenhouse gas 300 times more potent than CO_2.[8] Ammonia transport contributes a further ∼30 Mt CO_2 equivalent.[7] Altogether, fertilizers account for 1,100−1,300 Mt CO_2e annually, emphasizing that while decarbonizing ammonia production is critical, mitigating downstream N_2O emissions remains the greater long-term challenge.[2,7]

Nitrogen fertilizer use has profound impacts on both water and air quality.[5] Excess nitrogen leaches into water bodies, where it drives eutrophication, harmful algal blooms, and nitrate contamination of drinking water.[9−11] At the same time, fertilizer application releases reactive nitrogen compounds such as ammonia into the atmosphere, contributing to particulate matter formation and ozone pollution.[12,13]

Despite growing momentum toward decarbonizing ammonia production,[6] its water use and water scarcity risks remain poorly understood. Large volumes of water are needed not only for hydrogen production—a key feedstock for ammonia production,[14−17] but also for cooling, steam generation, and other auxiliary processes.[18,19] Water resources differ fundamentally from other industrial inputs in ways that make their

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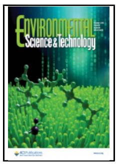

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risks particularly acute but often overlooked. Unlike energy or raw materials, water is nonsubstitutable, spatially constrained to local basins, and subject to strong seasonal and interannual variability.[20] Industrial withdrawals are also limited by ecological regulations and competition, especially in water-scarce regions where agricultural and domestic needs take precedence.[21] These unique characteristics mean that even when water is physically present, ammonia plants may face curtailments to preserve aquatic ecosystems or municipal supply.

Previous research has demonstrated the critical role of water in sustaining both food and energy systems. Water scarcity constrains rainfed[22,23] and irrigated agriculture[24−26] and limits energy production.[20] A growing body of studies has quantified water risks for power,[27−29] carbon capture and storage,[30,31] fossil fuel extraction,[32,33] and hydrogen production,[17,34] showing that water shortages can force facilities to curtail or suspend operations during droughts. Moreover, water use in the energy sector creates competition with other human demands and ecosystems, reinforcing inequalities in access.[21]

Despite this evidence, ammonia production, an equally water-intensive and strategically vital industry, has received far less attention. The sector's reliance on 406 large, geographically concentrated plants with inflexible operating schedules[6] exacerbates vulnerability, as facilities cannot easily adapt to local water constraints. Water scarcity can therefore directly curtail ammonia production, reducing fertilizer output and tightening supply−demand balances, which drives up prices. Higher fertilizer costs disproportionately affect farmers in the Global South, who are often unable to maintain application rates under price shocks. Reduced fertilizer use lowers crop yields, constraining agricultural output and deepening food insecurity. This cascade from water scarcity to production curtailment, price increases, and yield declines underscores the systemic vulnerability of global food systems to fertilizer supply disruptions. A substantial body of literature confirms that shocks to fertilizer supply and prices consistently translate into measurable impacts on crop yields and food security.[35−39,40]

Historical cases illustrate these risks in practice: the 2018 Rhine River drought forced BASF's Ludwigshafen facility to reduce ammonia output due to low river levels;[41] the 2011 Texas drought led to restrictions on fertilizer plants to safeguard municipal supplies;[42] and in 2021, water and power shortages in Sichuan prompted fertilizer plant shutdowns.[43]

In this study, we present a global assessment of the water use and water scarcity risks associated with ammonia fertilizer production, and explore how these risks propagate through international ammonia fertilizer trade and agricultural supply chains. This study extends previous work,[1,3] which focused on energy and trade dependencies, by adding water scarcity as a distinct analytical dimension and performing facility-level hydrological assessments. By identifying regions where water scarcity could emerge as a constraint, our analysis provides a complementary perspective that cannot be captured by existing frameworks, offering actionable insights for strengthening resilience in fertilizer supply chains and global food systems.

First, using life cycle analysis (LCA), we quantify the water consumption of ammonia production technologies. Second, drawing on new data that encompasses the complete global set of 406 ammonia production facilities, including their location, production capacity, and technology,[3] we evaluate their water consumption. Third, using a water balance model,[25,26] we map facility-by-facility monthly exposure to water scarcity. Fourth, using system engineering and international trade data of ammonia fertilizers, we identify key countries where water scarcity in fertilizer production translates into vulnerability for downstream food systems. Finally, we assess how many people are fed by crops grown using fertilizers produced under water-scarce conditions, both domestically and for export. The focus of this paper is specifically to highlight that, among the many trade-offs to consider when decarbonizing ammonia and improving its resilience, water should also be included as a key dimension. In this article, we explain why accounting for water is critical, outline how such an assessment can be conducted, and discuss its implications. Evaluating additional systemic risks, such as those related to energy, materials, labor, or fossil fuel dependency, lies beyond the scope of the present study.

■ METHODS

The methods are structured as follows. First, environmental LCA quantifies the water consumption associated with ammonia production. Second, water scarcity is assessed by mapping facilities against regional water stress. Third, the number of people fed by ammonia fertilizers is then estimated using country-specific nitrogen use efficiency and dietary needs. Finally, trade flows are analyzed with international trade data to track global fertilizer supply chain.

Life Cycle Analysis to Quantify Water Consumption of Ammonia Production. Environmental LCA[44] is used to quantify the direct and indirect water consumption of ammonia production. Our analysis is a cradle-to-gate analysis that includes all upstream processes up to ammonia. The application of ammonia is excluded from this analysis. The ecoinvent (v3.10) database[45,46] serves as the background life cycle inventory (LCI) database for calculating LCA results using *brightway2*.[47] Additional life cycle inventories of ammonia and hydrogen production are imported from *premise*.[48] The ReCiPe 2016[49] impact assessment method is applied to quantify life cycle water consumption.

The following conventional ammonia production pathways are considered: ammonia produced from steam methane reforming and from coal gasification.[18,48] Many inventories on hydrogen and ammonia production have been created in previous studies.[18,48] However, water consumption in environmental LCA needs careful validation to ensure water consumption is accurately balanced and reported. Therefore, we adopt the values of Nguyen et al.[50] for the direct water consumption for nitrogen production, using a value of 4.8 kg H_2O per kg of N_2. Similarly, for the Haber-Bosch process, we adopt a direct water consumption rate of 1.1 kg H_2O per kg of NH_3, also from Nguyen et al.[50]

It is worth noting that a distinction is made between direct and indirect water consumption. Direct water consumption refers to the water used on-site at the ammonia production facility. This includes water required for producing hydrogen (e.g., via coal gasification or natural gas reforming), producing nitrogen (typically from air) via an air separation unit, and operating the Haber-Bosch synthesis process. Indirect water consumption encompasses the water used throughout the broader supply chain, often in different geographies other than that of the actual production facility. This includes the water embedded in producing and transporting raw materials (e.g., steel and concrete) for facility construction, generating grid electricity used in the facility, and the upstream water impacts associated with fuel production. However, in this analysis, only on-site direct water consumption is considered because we are interested in local water scarcity assessment.

Our analysis assumes uniform direct water consumption across all ammonia production plants due to data limitations and does not account for facility- or technology-specific variations. Future research would benefit from more detailed data sets to refine location- and process-specific estimates. In our water scarcity assessment, we focus exclusively on direct water consumption because indirect water use, associated with inputs such as infrastructure, electricity, and fuel, is difficult to attribute to individual facilities, as these components are often produced abroad and traded internationally. By relying on direct water use, which can be consistently linked to the geographic location of each ammonia facility, our approach provides a robust basis for evaluating site-level exposure to water scarcity.

Inventory of Ammonia Production Facilities. To assess the direct water consumption of ammonia production facilities, we leveraged a novel, comprehensive global data set detailing the location and production capacity of existing ammonia facilities.[3] This data set includes 406 facilities worldwide, representing a total annual nominal installed capacity of 211 Mt NH_3 (100% of total ammonia production capacity installed globally). It was compiled by integrating information from multiple public and proprietary sources.[51−53] What sets this data set apart is its rigorous validation: each facility's location was confirmed through satellite imagery inspection, and production capacities were cross-verified with company reports where available.[3] This makes it the most spatially detailed and validated global inventory of ammonia production to date.

Water Scarcity Assessment. The goal of the study is to assess physical water scarcity, without accounting for water quality, infrastructure, or economic and institutional constraints, which are beyond the scope of this analysis. Water scarcity is defined as a condition in which total monthly human water consumption exceeded locally available water after accounting for environmental flows.[54] A facility was defined as exposed to water scarcity in a given month if the 50 km grid cell of the global water balance model in which it is located showed water consumption exceeding renewable water availability.[26,55] The 50 km spatial resolution represents the native resolution of the global water balance model used in this study.[26,55] In the analysis, the terms "grid cell" and "grid pixel" are used interchangeably to refer to this spatial unit. Based on this pixel-level analysis, we determined the number of water-scarcity months per year for each facility and estimated the share of production at risk by multiplying these months by the facility's monthly ammonia output.

Water scarcity exposure was assessed at a 30 arc-minute spatial resolution using a water balance model.[55−57] Renewable water availability was calculated as the residual of monthly available surface and subsurface water volumes after subtracting environmental flow requirements[54] and was spatially accumulated using a flow-routing module to preserve upstream−downstream hydrological connectivity.

To capture hydroclimatic variability, we used an ensemble of 20 simulations combining two global hydrological models (H08 and WaterGAP2−2e) with five CMIP6 (Coupled Model Intercomparison Project) global climate models (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1−2-HR, MRI-ESM2−0, and UKESM1−0-LL) under two Shared Socioeconomic Pathways (SSP1−2.6 and SSP5−8.5), with fixed socioeconomic conditions from 2015.[58] We selected SSP1−2.6 and SSP5−8.5 as they represent two divergent futures: a low-emission sustainability pathway consistent with limiting warming to well below 2 °C (SSP1−2.6) and a fossil fuel−intensive, high-emission trajectory leading to >4 °C warming by 2100 (SSP5−8.5).[59]

Monthly runoff (surface and subsurface) and irrigation water consumption data were obtained from the ISIMIP3b data set,[58] which includes harmonized simulations across all model combinations. We focused on the 2020−2029 period, treating 2025 as a representative year. Since ISIMIP3b simulations diverge from 2015 onward, bias correction was performed using year 2015 as the common baseline, ensuring consistency across ensemble members. This bias-adjustment method was applied both to runoff and to irrigation water consumption, following a delta-change approach in which projected differences were applied to harmonized reference values.

Other human water consumption was modeled as the total monthly demand from livestock, electricity generation, domestic use, mining, and manufacturing sectors. These sectors were selected because together they account for the largest contribution to direct human water use beyond irrigation, representing close to 100% of the anthropogenic water footprint.[60] Livestock and domestic use are the dominant nonirrigation consumptive uses globally, while electricity generation, mining, and manufacturing represent major industrial water demands. Including all of them ensures that our analysis captures the full range of human water consumption across agricultural, urban, and industrial activities. Sectoral demands, except for irrigation, were held constant at 2015 levels, based on the global data set by Huang et al.[61] For this analysis, ammonia production water consumption was introduced as an additional sector. We assessed facility-specific monthly direct water consumption by multiplying life cycle direct water consumption times monthly ammonia production at each facility. For each ammonia production facility, annual water consumption estimates were evenly distributed across all 12 months, assuming constant monthly operation throughout the year. If multiple ammonia production facilities were located within the same 30 arc-minute grid cell (50 km at the Equator), their monthly consumptions were aggregated, and the total cell-level ammonia−water demand was computed as the sum of all facilities contributions within that cell.

Quantifying People Fed by Ammonia Fertilizers. After quantifying facility-specific exposure to water scarcity, we assessed the number of people fed by food grown with fertilizers from ammonia produced with and without water scarcity conditions. Nitrogen fertilizers are the building block of amino acids, which are essential for the synthesis of proteins−fundamental nutrients for human sustenance. Because of this direct link between nitrogen and dietary protein, it is possible to estimate how many people are fed by the nitrogen used in agriculture. Each facility's output in kilo tonnes (kt) NH_3 yr^{-1} was converted to kt of nitrogen (N), accounting for molar mass (17.031 g/mol for NH_3, 14.007 g/mol for N) and assuming an 86% capacity factor for each facility.[62,63] This conservative lower-bound estimate reflects the typically high utilization rates of ammonia production plants, which are generally designed to operate continuously at 86−96% of capacity throughout the year.[62,63] This estimate is supported by cross-checking reported production and installed

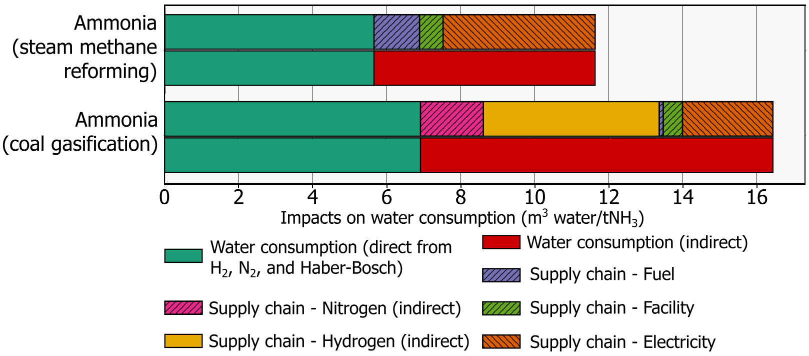

Figure 1. Water consumption of ammonia production via natural gas steam methane reforming and coal gasification. The figure illustrates the global average direct and indirect water consumption. Direct water consumption is used in the remaining analyses to assess water consumption and water scarcity at the facility level. We apply a single global, "average" water intensity (distinguished between both ammonia production pathways) across all geographical locations. The "Supply chain" labels indicate indirect water use associated with the specific supply chain process to produce ammonia.

capacity for facilities in the United States and Canada, the only regions with both sets of data available, which confirmed that an 86% capacity factor provides a reasonable representation of actual plant operation.[64] Downtime is generally limited to planned maintenance, which occurs during scheduled turnarounds approximately every four years and usually lasts about one month. Based on global fertilizer use statistics, we assumed that 70% of ammonia produced is allocated to agriculture.[3] The Food and Agriculture Organization reports an agricultural nitrogen fertilizer production of approximately 125 Mt N in 2020,[72] equivalent to roughly 150 Mt NH_3. Multiple sources, including the International Energy Agency,[6] indicate that around 70% of total ammonia is used in agriculture. Based on this share, total global ammonia production can be estimated as 150 Mt NH_3 ÷ 0.7 ≈ 217 Mt NH_3, which aligns closely with the aggregated installed capacity of 406 ammonia facilities, estimated at 211 Mt NH_3.[3] The total N available from ammonia for fertilizers use at each plant ($N_{ag,j}$) was therefore calculated as (1)

$$N_{ag,j} = 0.70 \cdot \mathrm{NH}_3^{\mathrm{prod},j} \cdot \frac{14.007}{17.031} \cdot 0.86 \tag{1}$$

Where j represent a facility. These quantities were aggregated at the country and global levels, and the share produced under water scarcity was determined based on each plant's location and local water scarcity.

Following the methods of Rosa and Gabrielli,[1] we then converted available nitrogen in each producing country (i.e., the sum of all national plants production, $N_{ag,j,i}$) into an equivalent number of "people fed" per country (F_i) based on country-specific nitrogen use efficiency (η_i), annual per capita protein intake (I_i), average farm-to-fork N yield (γ) and average N content of protein (ρ) (2)

$$F_i = \frac{\sum N_{ag,j,i} \cdot \eta_i \cdot \gamma}{I_i \cdot \rho} \tag{2}$$

Nitrogen use efficiency (η_i) represents the fraction of applied nitrogen that is used by crops during photosynthesis. It is calculated as the ratio of nitrogen uptake by crops to the total nitrogen applied.[65] This metric captures how efficiently fertilizers are utilized in each country, with lower values indicating higher nitrogen losses to the environment. Data for 161 countries and territories was collected from Lassaletta et al.[65] For the few cases where data was missing (specifically Taiwan and Côte d'Ivoire), we replaced the values with the average calculated across all other countries and territories with nonmissing data.

Farm-to-fork nitrogen yield (γ) accounts for losses throughout the food supply chain—from production to consumption.[66,67] We adopt a global average of 42.5%, based on prior estimates ranging from 41% to 44%.[66,67] This factor reflects inefficiencies such as harvesting losses, postharvest waste, nonfood uses, processing and packaging losses, distribution inefficiencies, and food waste at the consumer level.

Nitrogen content of protein (ρ) is assumed to be 18%,[68] a standard biochemical factor reflecting the average nitrogen proportion in edible proteins. For nitrogen used domestically, we applied the producer country's efficiency and dietary parameters. For nitrogen being exported and used abroad, we applied nitrogen use efficiency and protein intake of the importing country. Annual per capita protein intake (I_i) represents the average amount of protein consumed by an individual in a given country each year. This value varies widely across countries and is crucial in estimating how much nitrogen is required to meet national dietary needs. Data for 155 countries was sourced from the Food and Agriculture Organization.[69] In the eight countries and territories where data was unavailable (i.e., Bahrain, Bermuda, Brunei Darussalam, Cook Islands, Eritrea, Nauru, Qatar, and Tonga) we substituted missing values with the average calculated across all other countries with available data.

Ammonia Fertilizers Trade. International trade data for N fertilizers was collected from World Bank Comtrade data (2022)[70] under product code 3102: "Mineral or chemical fertilizers, nitrogenous", providing a country-to-country trade matrix by both value and weight. Reported global trade in fertilizer products was cross validated with the Observatory of Economic Complexity data.[71] To harmonize all flows by nitrogen content, we used estimates from the Food and Agriculture Organization of the United Nations of 45 Mt N traded globally in 2022,[72] assigning an average N content of 47% by weight to all trade routes (in the absence of more granular product breakdowns). This produced a comprehensive matrix of annual N flows (in tonnes) for all trade routes.

To determine how much nitrogen each country uses domestically and how much it exports, we grouped trade flows to obtain annual N imports ($N_{\mathrm{imp},i}$) and exports ($N_{\mathrm{exp},i}$) for each country i. As many countries are both importers and

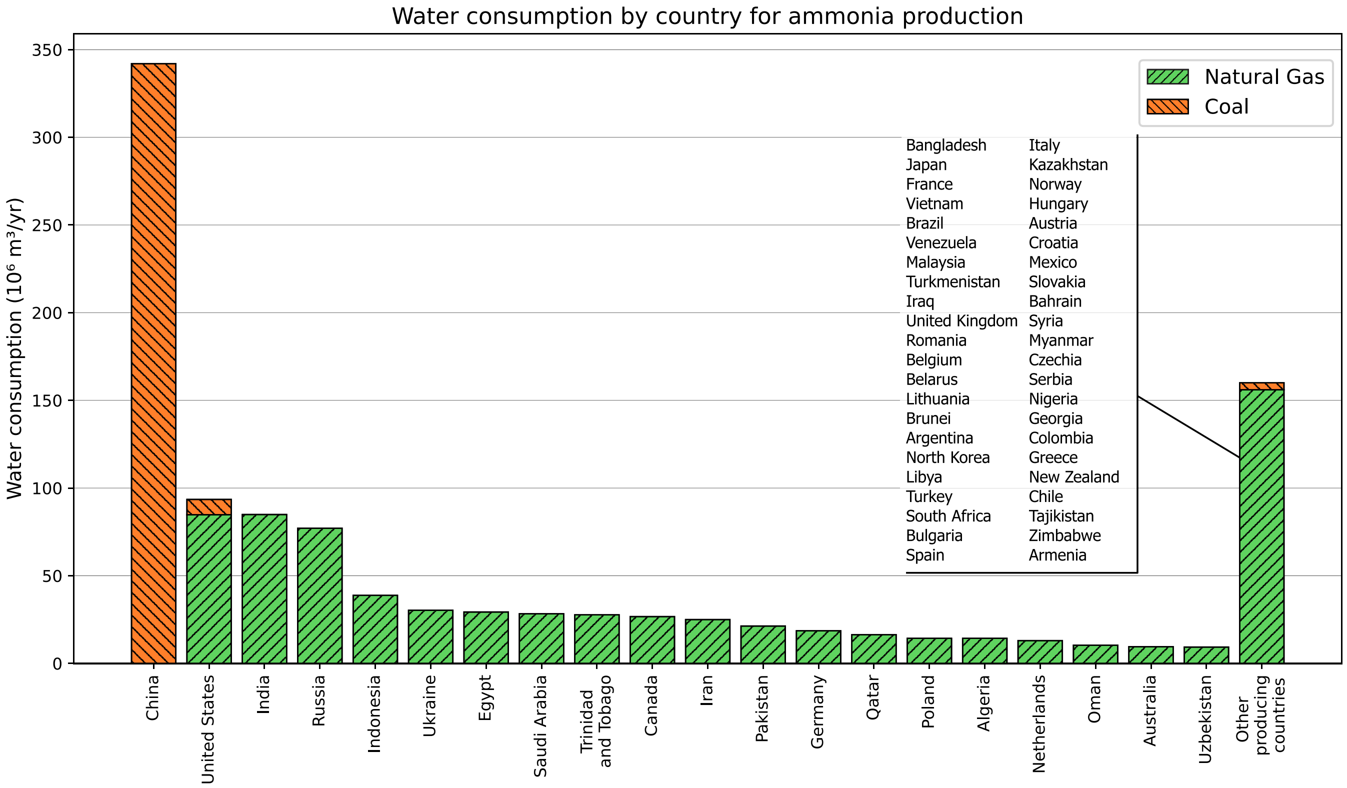

Figure 2. Estimated direct water consumption for ammonia production by country (million m^3 yr^{-1}). Bars are colored according to the share of facilities fed by natural gas (steam methane reforming-based ammonia production) (green) and coal gasification-based ammonia production (orange). Countries are sorted by direct water consumption, with only the top 20 producers shown individually. The remaining countries are aggregated under “Other producing countries”.

exporters, we first calculated the trade balance for each. In cases where reported N exports exceeded total national production dedicated to agriculture ($\sum N_{ag,j,i}$), we capped exports to the country’s actual production (3). The remaining N was counted as used domestically (4)

$$N_{\text{exp},i} = \min\left(N_{\text{exp,reported},i}, \sum N_{ag,j,i}\right) \tag{3}$$

$$N_{\text{dom},i} = \sum N_{ag,j,i} - N_{\text{exp},i} \tag{4}$$

This ensures that a country cannot export more nitrogen than it produces.

For each country, the share of ammonia fertilizers produced under water scarcity was determined from facility-level data and mapped to both domestic and exported N under the assumption of national-level mixing (i.e., the same fraction applies to both streams). This is necessary since fertilizer trade is tracked at the national, and not at the facility level.

For exported N, the share produced under water scarcity is incorporated in the trade flow, regardless of the importing country.

RESULTS

Water Consumption Intensity. Figure 1 shows the water consumption of two conventional large-scale ammonia production pathways using coal gasification and steam methane reforming technologies. The stacked bar chart illustrates the life cycle water consumption per metric ton of ammonia (t NH_3) produced. Each bar segment represents a specific contribution to the total water intensity. Figure 1 illustrates that ammonia production via coal gasification consumes approximately 16 m^3 per t NH_3, resulting in a higher total life cycle water footprint compared to the steam methane reforming pathway, which uses about 12 m^3 per t NH_3. The higher water consumption in the coal pathway is primarily driven by indirect water use, particularly from electricity demand and water-intensive coal extraction processes along the coal supply chain. Direct water consumption is also slightly larger for coal-based ammonia production, around 7 m^3 t NH_3^{-1}, compared to steam methane reforming-based production at nearly 6 m^3 t NH_3^{-1}. These direct water demands originate from hydrogen production, the Haber-Bosch process (~1.1 kg H_2O per kg NH_3), and nitrogen production (~4.8 kg H_2O per kg N_2).

Water Consumption of Ammonia. We estimate water consumption for 406 ammonia production facilities by multiplying the direct water consumption intensity of each production pathway by the facility-specific ammonia output. Figure 2 represents direct water consumption for ammonia production by country, distinguishing between natural gas and coal-based ammonia production pathways. The histogram highlights the top 20 ammonia-producing countries along with the rest of the producers (“Other producing countries”). Globally, direct water consumption for ammonia production is estimated at 1.09 billion m^3 per year, with approximately 67% of water consumption from steam methane reforming and the remaining 33% from coal gasification (Figure 2). China is by far the largest water consumer, using approximately 342 million m^3 of water annually, primarily due to its reliance on coal gasification, and its large production volume. In contrast, other top producers such as the United States (94 million m^3 per year, 9% reliance on coal gasification), India (85 million m^3

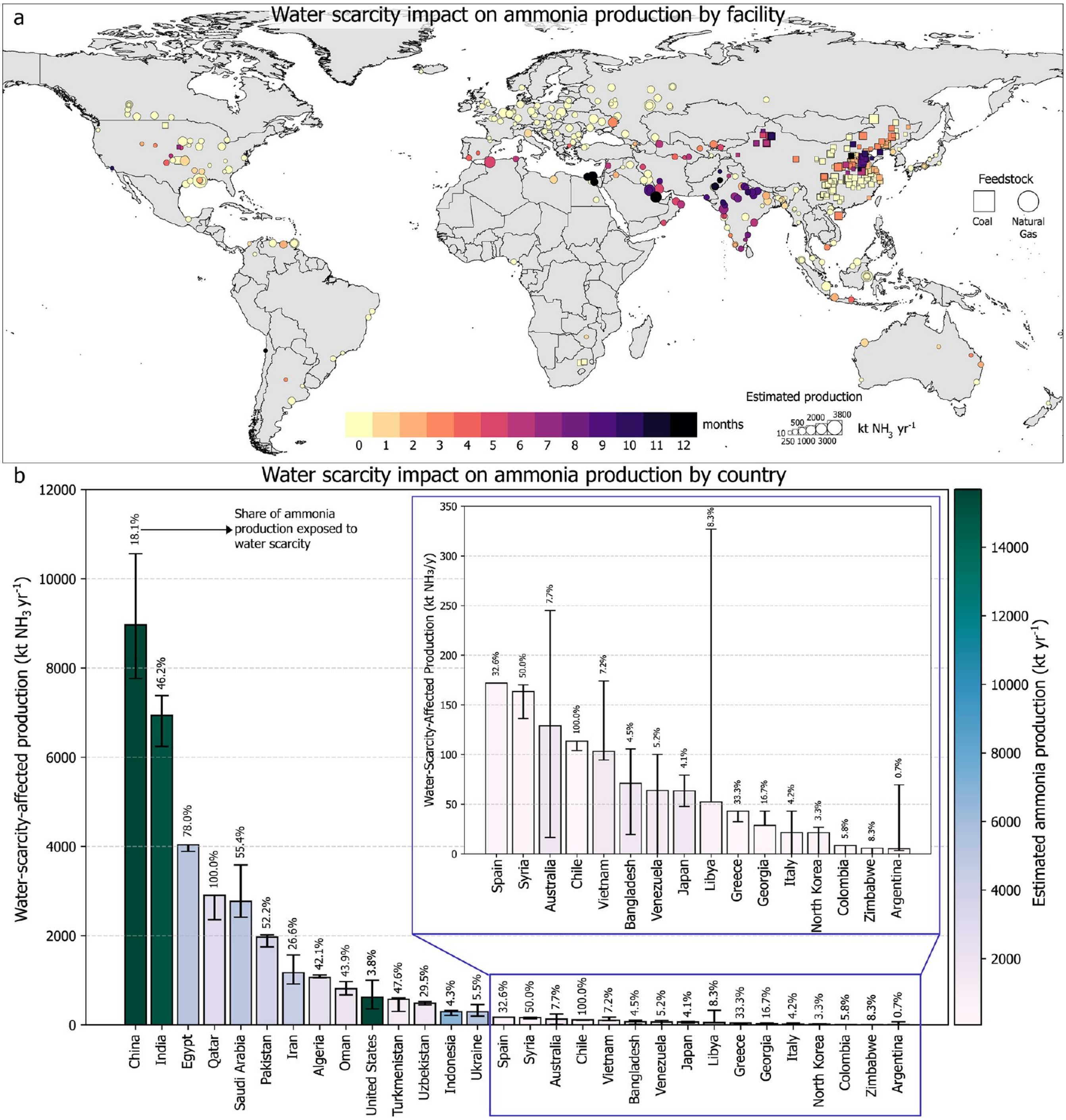

Figure 3. Water scarcity exposure to ammonia production. (a) Global distribution of ammonia production facilities, with the colors indicating the number of months per year affected by water scarcity. The marker shapes denote feedstock type (circle: natural gas; square: coal), and size reflects estimated annual production capacity (kt NH_3 yr^{-1}). (b) Country-level aggregation of water-scarcity-affected ammonia production (kt NH_3 yr^{-1}), with bars colored by total estimated national production. Interval bars illustrate interquartile ranges across plants within each country according to the ensemble of 20 combinations between two hydrological models (H08 and WaterGAP2−2e), five climate models (IPSL-CM6A-LR, UKESM1−0-LL, GFDL-ESM4, MPI-ESM1.2-HR, and MRI-ESM2.0), and two climate scenarios (SSP1−2.6 and SSP5−8.5). Numeric labels above each bar indicate the median percentage of total ammonia production exposed to water scarcity in each country. The inset highlights additional countries with smaller but non-negligible affected production.

per year), and Russia (77 million m^3 per year) predominantly rely on natural gas. Other countries include Indonesia (39 million m^3 per year), Ukraine (30 million m^3 per year), and Egypt (29 million m^3 per year), all with fully natural gas-based ammonia production.

Facility-Specific Water Scarcity Exposure. Figure 3 illustrates the global exposure of ammonia production to water scarcity conditions in terms of the number of affected months by facility (Figure 3a) and by country (Figure 3b). In the geospatial map (Figure 3a), each point represents an individual ammonia production facility, with the shape indicating the

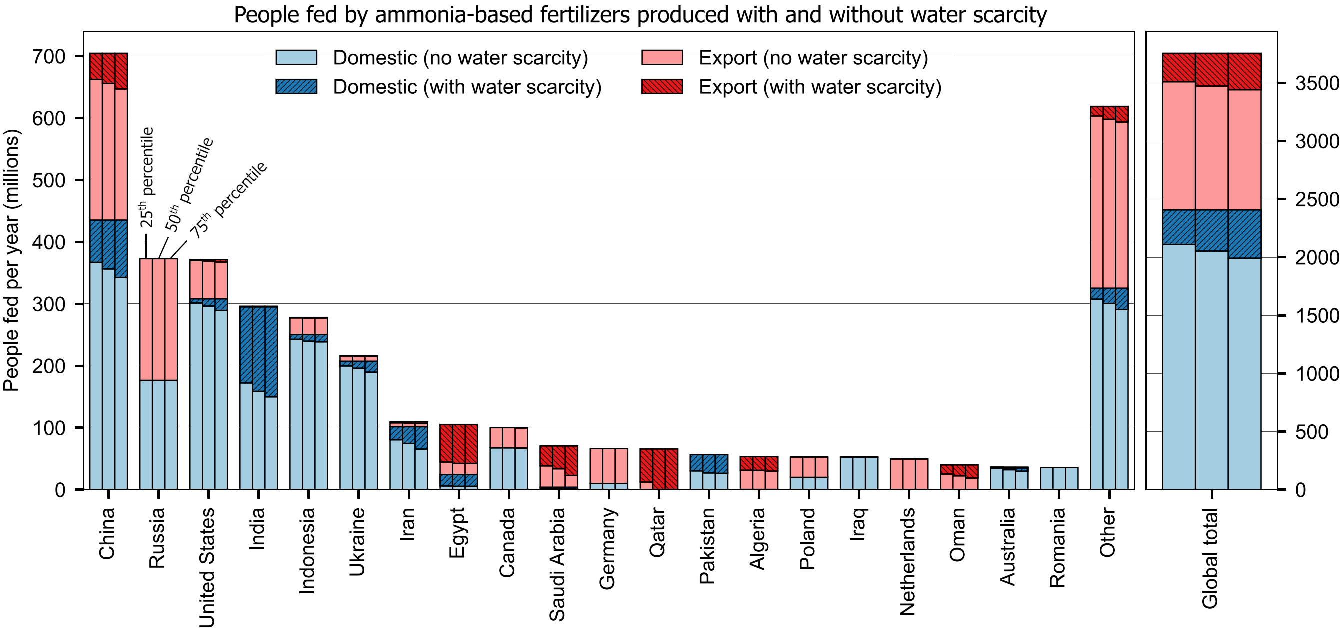

Figure 4. The 20 countries with the largest population fed with ammonia fertilizers production, disaggregated by water scarcity exposure and domestic and export use. Bars distinguish between ammonia fertilizers produced and used domestically (blue shades) and for export (red shades), with hatched bars indicating production under water scarcity. For each country, three adjacent bars represent the 25th percentile, median, and 75th percentile estimates, reflecting uncertainty in water scarcity exposure based on the interquartile range from hydrological variability in water scarcity assessment.

feedstock type and production technology (circles for natural gas steam methane reforming, squares for coal gasification) and the size proportional to the plant estimated annual production capacity (in kt NH_3 yr^{-1}). Facilities in Europe, North America, and Southeast Asia experience less than three months or no water scarcity, indicating limited hydrological stress under current production conditions. In contrast, clusters of facilities in North Africa, the Middle East, Northeast and South Asia exhibit markedly higher exposure, with several sites facing 6–12 months of water scarcity per year (Figure 3a).

Production Affected by Water Scarcity. Figure 3b presents the country-level aggregation of ammonia production affected by water scarcity, highlighting both ensemble median and interquartile range across producing countries. We find that 18% (33 Mt ammonia per year; interquartile range: 16–21% among models) are in water scarcity for at least a month per year. The largest absolute impacts are observed in China and India, where an estimated 9 and 6.9 Mt NH_3 yr^{-1}, respectively, are potentially exposed to operational disruptions, corresponding to 18% and 46% of their total national production, respectively. Other major producers such as Egypt, Pakistan, Qatar, and Saudi Arabia also exhibit high levels of exposure, with affected capacities often exceeding 52–100% of national totals (Figure 3b). In contrast, countries among the top 10 ammonia producers, such as the United States, Russia, Trinidad and Tobago, and Canada, reveal no or only limited exposure to water scarcity. For example, in the United States, only 4% of total ammonia domestic production (equivalent to approximately 618 kt NH_3 yr^{-1}) is potentially exposed. Smaller producers show disproportionately high relative exposure, such as Algeria, Iran, Oman, and Turkmenistan, where over 27–48% of national production may be at risk (Figure 3b). Libya stands out due to its highly skewed interquartile range (Figure 3b), with a low median exposure (1 month; 52 kt NH_3 yr^{-1}) but a 75th percentile reaching 6 months (327 kt NH_3/yr), reflecting substantial interannual variability in water scarcity conditions and underscoring the risks of relying on a single, high-capacity facility in a hydrologically volatile environment.

People Fed from Ammonia Fertilizers. By integrating data on fertilizer production, international trade, dietary patterns, and fertilizer use efficiency, we estimate the number of people supported by food grown with ammonia-based fertilizers—focusing on fertilizers produced in water-scarce regions. Figure 4 illustrates the number of people fed by food grown with ammonia fertilizers, distinguishing between those produced in water-scarce versus water-abundant regions, and whether the fertilizers were used domestically or exported. The results are presented for the median and interquartile scenarios based on 20 combinations of hydrological and climate models and emissions pathways, highlighting the impact of hydrological variability on the estimates.

Globally, 70% of ammonia production is used to grow food that feeds 3.8 billion people.[1,3] Of these, 2.4 billion people rely on food produced with domestically manufactured fertilizers, while the remaining 1.4 billion are fed through food grown using fertilizers intended for export (Figure 4). Our analysis reveals that 637 million people worldwide, approximately 18% of the total, depend on food grown with ammonia fertilizers produced in regions experiencing water scarcity (Figure 4). This estimate varies from 545 to 730 million people (15–19%) across 20 combinations of hydrological and climate models and emissions scenarios (Figure 4). Of this total, 355 million people (interquartile range: 300–417 million) are supported by domestically consumed fertilizers produced under water-scarce conditions. The remaining 282 million people (interquartile range: 245–314 million) rely on food grown using imported fertilizers produced under water scarcity risks (Figure 4). These cross-border fertilizer flows effectively

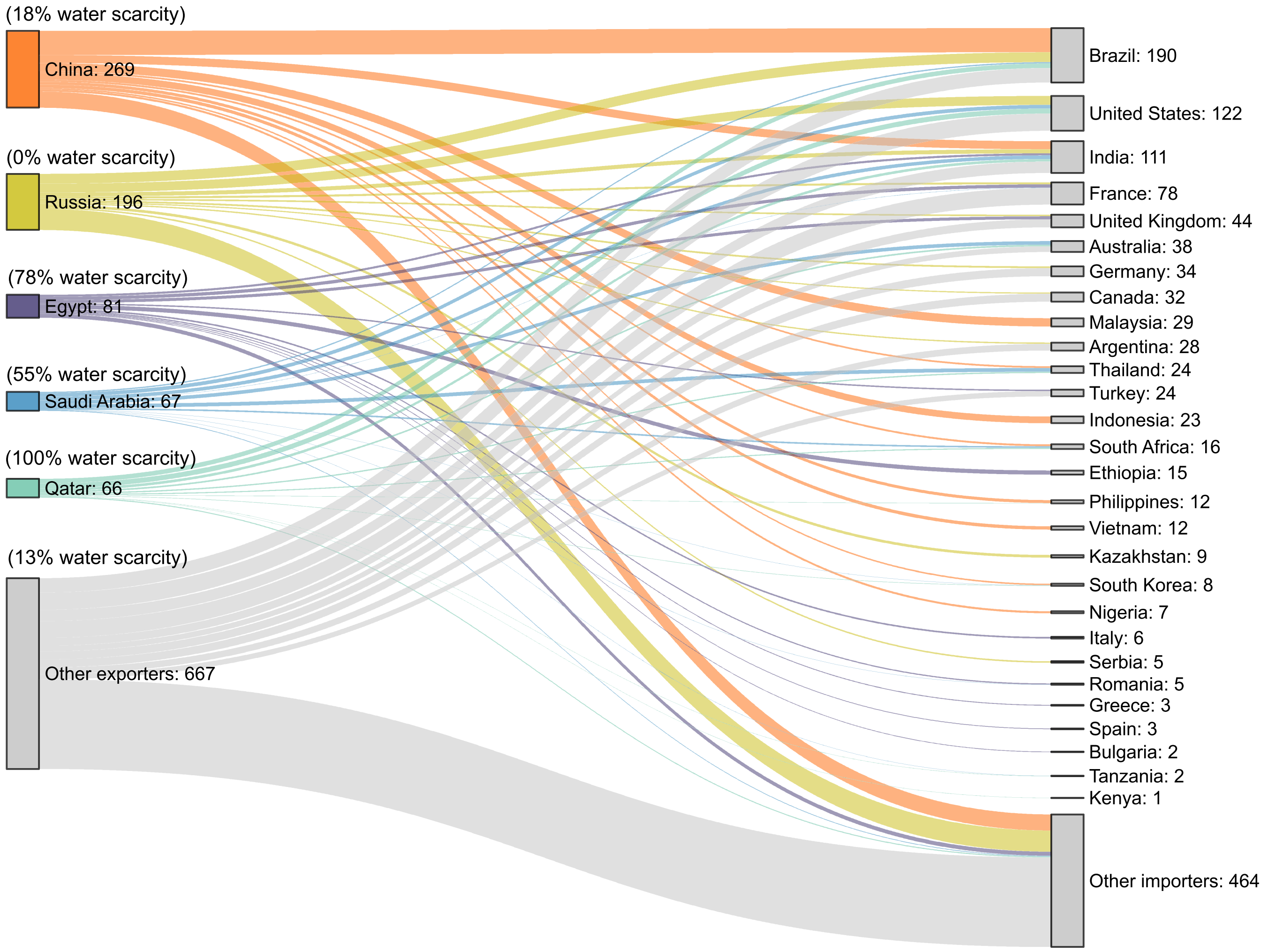

Figure 5. Major global trading partners of ammonia-based fertilizers. Top 5 fertilizer exporting countries by total people fed (in millions), showing their main import partners. Values in parentheses indicate the share (%) of those people whose food production is linked to fertilizer produced facing water scarcity.

transfer water stress internationally, embedding environmental burdens within global food supply chains.

Figure 4 also presents results at the country level. Ammonia fertilizers produced in China support food production for 705 million people, with 62% used domestically and the remainder contributing to food systems abroad through exports. In China, 79 million people (interquartile range: 68−93 million) are fed with food grown using fertilizers produced under water-scarce conditions, while 49 million people (interquartile range: 42−57 million) in other countries are fed through imports from China (Figure 4).

Russia and the United States follow, each contributing to the food supply of approximately 370 million people, primarily through exports and largely without exposure to water scarcity in their ammonia production. India and Indonesia are also major contributors, feeding 296 million and 278 million people, respectively. India's food production is highly reliant on domestically produced nitrogen, with a substantial share (42−49%) originating from regions facing water scarcity. As a result, India is the largest contributor to the population fed using fertilizers produced under water-scarce conditions—accounting for 137 million people (interquartile range: 123−146 million). Egypt is another major producer of ammonia fertilizers in water-scarce regions feeding 82 million people, followed by Qatar (66 million people), Saudi Arabia (39 million people), Pakistan (30 million people), and Iran (29 million people).

Trade Flows of Ammonia Fertilizers. By analyzing trade flow data for ammonia fertilizers, we estimate the number of people reliant on trade and mapped key trade routes, revealing the extent of global reliance on fertilizers produced in water-scarce regions. Figures 5 and 6 illustrate these trade flows, showing the number of people fed through each route—both with and without exposure to water scarcity—and identifying countries that are most vulnerable to supply disruptions and water scarcity risks.

China, Russia, Egypt, Saudi Arabia, and Qatar collectively account for over half of the global population fed through fertilizer exports. China and Russia are the leading exporters of ammonia fertilizers, supporting the diets of 269 million and 196 million people, respectively (Figure 5). In China, 18% of fertilizer production occurs under water-scarce conditions, meaning that a proportionate share of importing countries' food supply is exposed to water scarcity risks (Figure 5). China mainly exports its fertilizers to Brazil, Malaysia, India, Indonesia, and Vietnam feeding 84, 29, 28, 23, 12 million people, respectively (Figure 5). Russia does not face water scarcity in production of ammonia and export its fertilizers to

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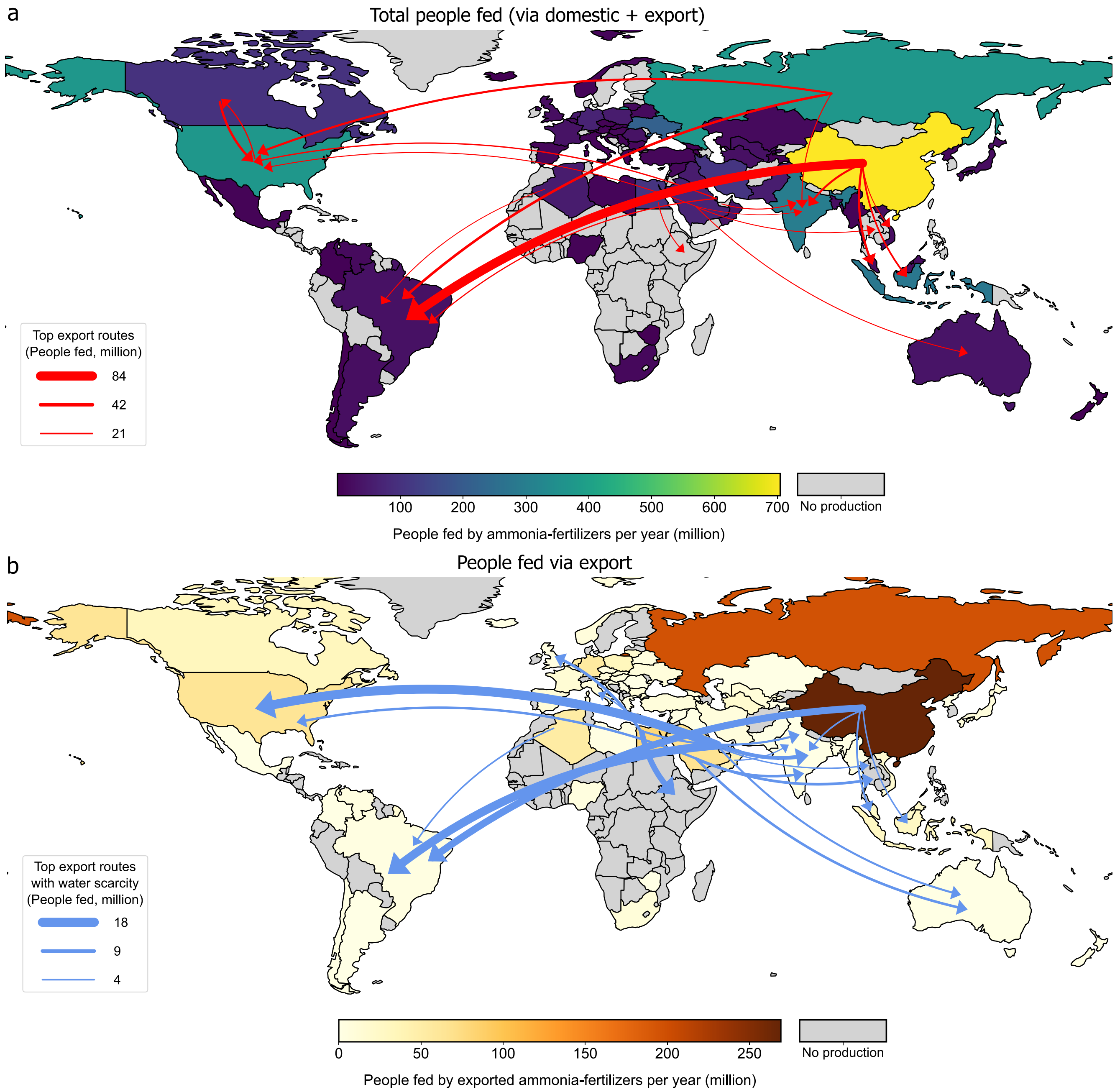

Figure 6. Global distribution of people fed by ammonia fertilizers production and largest trade routes. (a) Countries are color-coded by the total number of people fed (domestic + export), with arrows indicating the top 20 trade routes measured as people fed. (b) Countries are color-coded by the total number of people fed through export only, with the top 20 trade routes shown based on the number of people fed using ammonia fertilizers produced under water scarcity. Results are presented considering the median scenario among the 20 combinations between hydrological and climate models and scenarios.

Brazil, the USA, India, feeding 34, 31, 14 million people, respectively (Figure 5). Egypt, Saudi Arabia, and Qatar follow, supporting 81, 67, and 66 million people, respectively. Notably, a substantial share of their fertilizer exports is produced under water-scarce conditions—78% in Egypt, 55% in Saudi Arabia, and 100% in Qatar (Figure 5). On the import side, Brazil is the largest recipient, importing fertilizers that feed 190 million people. It is followed by the United States (122 million), India (111 million), France (78 million), United Kingdom (44 million), and Australia (38 million) (Figure 5).

Figure 6 highlights the top 20 ammonia fertilizer trade routes based on the number of people fed. Figure 6a presents total values, while Figure 6b focuses on the number of people fed using fertilizers produced under water-scarce conditions. The largest trade route is from China to Brazil, where Chinese-based ammonia fertilizers support the diets of 84 million people per year (Figure 6a). This is followed by exports from Russia to Brazil (34 million people per year), Russia to the United States (31 million), and Canada to the United States (31 million). Other significant routes include exports from China to Malaysia (29 million), India (28 million), and Indonesia (23 million). Notably, seven of the top eight trade routes involve China or Russia as the exporting country (Figure 6a).

When focusing specifically on trade routes involving fertilizers produced under water-scarce conditions, the largest is from Qatar to the United States, supporting 18 million people (Figure 6b). This is followed by Qatar-to-Brazil and China-to-Brazil route, which support 16 and 15 million people, respectively, and by additional exports from Egypt to Ethiopia (11 million people), Qatar to India (9 million), and Egypt to France (9 million). These patterns underscore the important role of water-scarce regions in exporting fertilizers that embed water stress into global food supply chains (Figure 6b).

DISCUSSION

Our results show that ammonia production faces facility-specific water scarcity risks that can propagate through global fertilizer supply chains, posing a secondary but critical threat to food security compared to agricultural water scarcity. Globally, ∼18% of ammonia production (∼33 Mt NH_3 yr^{-1}) is exposed to at least one month of water scarcity annually, with substantial impacts in China and India (18% and 46% of national production, respectively). Smaller producers, such as Egypt, Qatar, and Saudi Arabia, face even higher water scarcity risks (Figure 3). Because global ammonia production is concentrated in just 406 facilities, disruptions at a single large plant can reverberate across international markets, amplifying local water scarcity shocks into worldwide fertilizer supply constraints. Trade further magnifies these vulnerabilities: major exporters such as China, Russia, Egypt, Qatar, and Saudi Arabia supply more than half of the global population dependent on ammonia-based fertilizers, linking water scarcity in exporting basins to food production in importing regions (Figures 4−5). As a result, approximately 637 million people rely on food grown with fertilizers produced under water-scarce conditions (Figures 5−6). Local hydrological risks thus extend globally, shaping fertilizer costs, supply security, and ultimately food availability. The 2022 fertilizer price surge reduced Sub-Saharan African fertilizer use by 20−30%, lowering maize yields by 15% and raising global food prices 5−15%.[35]

Water scarcity affects supply chains in ways that differ from, for example, energy shortages. Water scarcity often forces governments to prioritize water for households over industry, making ammonia production plants more vulnerable. Because these plants are often clustered near rivers to secure significant amounts of water, a drought can disrupt multiple facilities simultaneously. As such, recovery is usually slower than for energy shocks since there are no water substitutes (as with energy), and restarting production may require (costly) inspections and regulatory approvals.

Many countries depend on food produced in water-stressed regions, where irrigation faces both physical constraints, limited renewable water availability[26,55] and socioeconomic or institutional barriers to sustainable management.[56,73] Irrigated croplands under water scarcity currently sustain about 1.3 billion people, with roughly 15% of unsustainable irrigation embedded in internationally traded commodities.[74,75] The concept of virtual water[76,77] underscores how local water scarcity is "exported" through trade, transmitting water risks from producing to consuming regions. Recent studies further highlight the central role of agro-food enterprises in shaping virtual water flows and advancing global water stewardship.[78−80]

Our analysis does not incorporate facility-specific water consumption, instead we apply a uniform direct water use assumption across all ammonia production plants due to data limitations. We adopt a single average and conservative estimate, distinguishing only between coal- and natural gas-based production, which inevitably overlooks variability arising from local operating conditions and technology differences. While this global averaging provides a consistent basis for comparison, it prevents identification of regional and facility-level differences in water use, meaning our assessment does not fully capture local variations. Future research should therefore leverage facility- and country-specific data sets, where available, to refine water scarcity assessments and provide more location-specific insights.

Although this study focuses on industrial ammonia production and its associated water risks, we acknowledge that ammonia use itself also imposes substantial environmental burdens. In the broader debate, some advocate for producing ammonia more sustainably, while others argue that both production and use should be reduced in agriculture to mitigate climate, air, and water impacts. Addressing these challenges requires improving nitrogen use efficiency in agriculture,[65] reducing food waste, and shifting toward less nitrogen-intensive diets,[1] alongside circular economy strategies such as nutrient recovery, recycling organic fertilizers,[81] and developing alternative fertilizer technologies.[82] These demand-side measures complement supply side decarbonization and are critical for reducing environmental impacts from nitrogen fertilizers.

Decarbonizing ammonia production is critical for meeting climate targets, particularly as many existing facilities are aging and in need of modernization.[6] While comprehensive life cycle assessments of low-carbon ammonia pathways are not yet available, previous studies indicate that blue ammonia (fossil-based production with carbon capture) or green ammonia (renewable-based) tend to be more water- and energy-intensive than conventional fossil-based production.[1,19,34] This potential for increased resource intensity raises concerns about exacerbating water stress.[34] These findings highlight the importance of carefully evaluating local resource constraints when deploying low-carbon ammonia technologies.[83]

Ammonia production's exposure to water scarcity represents a distinct and under-evaluated risk for global food security, particularly in regions reliant on imported fertilizers or concentrated production hubs. Previous work has demonstrated that spatially differentiated nitrogen supply is key in a global food−fertilizer price crisis.[84] To enhance resilience, strategies include siting new facilities in water-abundant areas, adopting decentralized small-scale systems that reduce geographical concentration of production,[85−87] or relocating production away from vulnerable regions, while integrating water availability into facility siting and operational decisions is critical for aligning decarbonization with broader sustainability objectives. Retrofitting plants with water-efficient technologies, such as closed-loop or air-cooling systems, can reduce freshwater use in water-stressed regions, while desalination offers an alternative source of industrial water but comes with important energy requirements and additional costs that could undermine the competitiveness of green ammonia. Diversifying production through new facilities in water-abundant areas or investments in small-scale decentralized green ammonia reduces geographic concentration risks.

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■ ASSOCIATED CONTENT

Data Availability Statement

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■ AUTHOR INFORMATION

Corresponding Author

Lorenzo Rosa − *Biosphere Sciences & Engineering, Carnegie Institution for Science, Stanford, California 94305, United States;* orcid.org/0000-0002-1280-9945; Email: lrosa@carnegiescience.edu

Authors

Andrea Citrini − *Biosphere Sciences & Engineering, Carnegie Institution for Science, Stanford, California 94305, United States*

Tom Terlouw − *Biosphere Sciences & Engineering, Carnegie Institution for Science, Stanford, California 94305, United States; Laboratory for Energy Systems Analysis, PSI centers for Nuclear Engineering and Sciences and for Energy and Environmental Sciences, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland; Chair of Energy Systems Analysis, Institute of Energy and Process Engineering, ETH Zurich, Zurich 8092, Switzerland;* orcid.org/0000-0003-3744-9728

Stefano Mingolla − *Biosphere Sciences & Engineering, Carnegie Institution for Science, Stanford, California 94305, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.5c14489

Author Contributions

L.R. conceived and designed the study. T.T. performed LCA analyses; A.C. performed hydrological analyses; S.M. performed trade and food security analyses. L.R. wrote the study with inputs from all authors.

Notes

The authors declare no competing financial interest.

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