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Indian interstate trade exacerbates nutrient pollution in food production hubs

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Intensive agricultural practices have powered green revolutions, helping nations attain self-sufficiency. However, these fertilizer-intensive methods and exploitative trade systems have created unsustainable agricultural systems. To probe the environmental consequences on production hubs, we map the fate of Nitrogen and Phosphorus in India's interstate staple crop trade over the recent decade. The nation's food bowls, while meeting national food demand, are becoming pollution-rich, sustaining around 50% of the total surplus from trade transfer, accounting for 710 gigagrams of nitrogen per year and 200 gigagrams of phosphorus per year. In combination with water balance analysis, surplus nutrient conversion to a graywater footprint further highlights an aggravated situation in major producer regions facing long-term water deficits. Given India's role in global food security, identifying the nation's environmental vulnerability can help in designing appropriate policy interventions for sustainable development.

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Sustainably feeding the growing global population is the contemporary challenge of humanity to achieve global food security[1,2]. Since the commencement of the green revolution, global agricultural systems have undergone a profound transformation in the context of technology and the application of fertilizers[3–5]. Agricultural intensification fueled by injudicious fertilizer consumption helped increase crop yields aligned with growing demand[1,6,7]. However, this increase in input intensity has an adverse effect on air[8], water quality[9], climate[10], and human health[10–12]. As the demand for agricultural crops intensifies due to a combination of factors, including a rising global population, evolving dietary preferences, and the use of crops for fuel, fodder, and animal feed, the anticipated environmental burden in terms of nutrient and water footprint is expected to particularly weigh on exporting nations compared to their importing counterparts[5,9,13,14]. Although various researchers[5,15] have reported the footprints of embedded nitrogen in global trade networks, a comprehensive and systematic environmental impact assessment in production centers is limited[16]. Network-based approaches informed by the underlying dynamics that account for spatiotemporal evolution and interaction are needed to provide information about the complex interaction among trade networks, consumption demand, nutrient surplus, and environmental sustainability.

Maintaining agricultural productivity requires replenishing the nutrients used by the harvested crops via external inputs, either through biological fixation or by adding mineral fertilizer or animal manure[17] (Fig. 1). Although an inadequate amount of nutrients will decrease crop productivity, excessive amounts can cause severe environmental issues such as groundwater contamination, soil acidification, and the release of greenhouse gases into the atmosphere[18]. In the entire agri-food chain, more than 80% of the Nitrogen (N) and Phosphorus (P) consumed ends up lost in the environment (Fig. 1)[10,19]. Researchers[20] have quantified the consequences of this exacerbating nutrient pollution, calling for the need to improve Nutrient use Efficiency (NuUE: ratio of the output of harvested nutrients (N, P) to the nutrients input) during crop production. Although much research[21,22] has been done on improving NuUE at the farm level (through the implementation of better nutrient management practices), only a few studies have examined the impact of changing NuUE on trade-driven nutrient pollution[23]. Policy discussions focusing on reducing the impact of nutrient pollution tend to focus on the management of applied fertilizer at the farm level, given its dominance as a source of pollution[24]. However, farmers are not the only actors in the agri-food chain that drive agricultural nutrient losses[19]; consumer demand plays an important role in driving this surplus of nutrients in agricultural states[25]. Therefore, it is necessary to explore the environmental burden of the traded agricultural commodities and related environmental pollution in already stressed agriculture systems[11].

Driven by the increased consumption of synthetic fertilizers, developing nations like India gained self-sufficiency in cereal production through the Green Revolution[26]. However, the consumption of imprudent water and fertilizers improved crop yield, ultimately creating an inherently unsustainable legacy of the agricultural system, urging the need for better synergy between food security and environmental stewardship in India[7]. Although nutrient transfer embedded in international trade helps identify nations with nutrient pollution[2,5,16,27,28], it generalizes the problem, hence missing out on specific regions of pollution hotspots. Moreover, researchers have focused on evaluating the physical and virtual quantities of networks that are traded nationally/globally and their impact on water resources[14,23,28–30] or have focused on the imbalance of N and P at the aggregate level[16,31]. However, a comprehensive spatiotemporally explicit nutrient footprint with detailed compartmentalization of macronutrients is not reported at a policy-relevant (sub-national) scale.

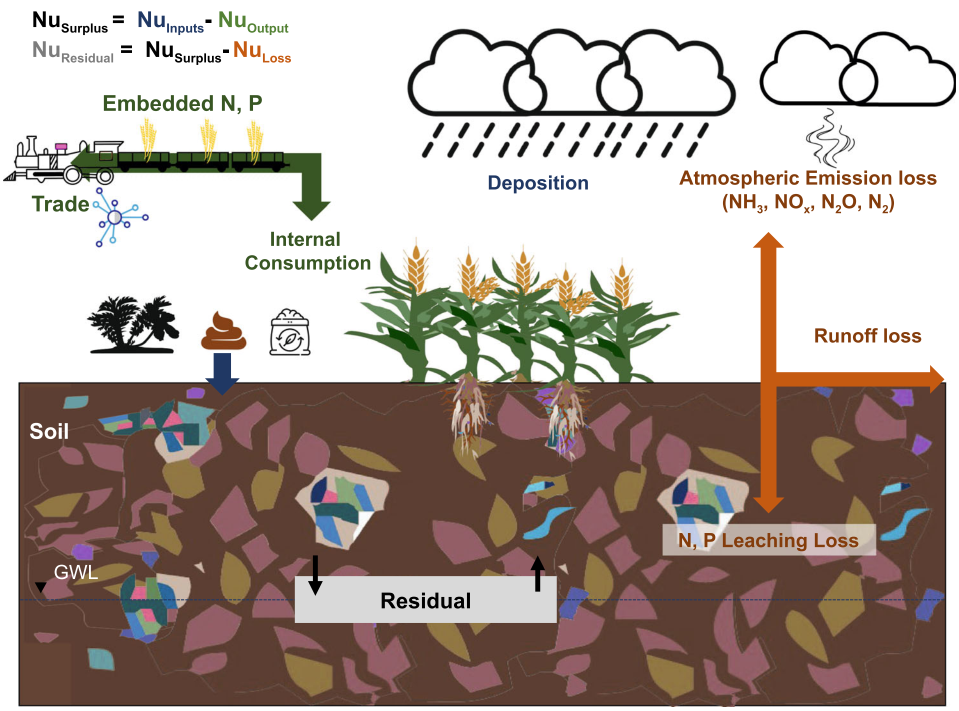

Fig. 1 Illustration of crop Nutrient (Nu) budget. The blue arrow shows the major input of nutrients (manure, biological fixation, fertilizer, and atmospheric deposition). The orange arrow represents the loss of nutrients in the form of leaching, runoff, and atmospheric emission, highlighting the potential nutrient losses from the system. The black arrow represents the internal nutrient cycle within the soil, emphasizing the recycling and reutilization of nutrients within the agricultural system. The green arrow represents the nutrient output, specifically the nutrient content in harvested crop production, which can be either traded or used internally by the state. In this study, our focus is specifically on the trade component of agricultural production.

While the role of the Indian states of Punjab and Haryana and their supremacy as leading producers and exporters in ensuring food security are well known[32], favorable growing conditions come at the cost of a sustained environmental burden for these states, which implicitly reduces the equivalent burden of consumer states[33,34]. Although there are monetary benefits for producing states, the lack of quantification of sustained accumulation (left-over nutrients) is the key driver of agricultural pollution and has kept discussions and policies around incentivizing these overheads at bay. Consequently, society pays hidden costs related to environmental pollution in the form of degraded ecosystems, contaminated water supplies, and polluted soil, resulting in a deviation from sustainability development goals (SDGs)[35]. Despite the scale of this problem, current policy discussions often fail to address it effectively, mainly because quantifying the total environmental costs of agricultural production requires a more holistic understanding of the interconnections between various pollution drivers and the roles of different actors in the agricultural supply chain. While our study does highlight the lack of attention to environmental costs in current policy discussions, we acknowledge, following the literature[36–38], that identifying and addressing such costs in policy involves complex socio-political dynamics. These dynamics include various stakeholder interests, existing institutional frameworks, and the political will to transform an issue into actionable policy. As such, the absence of comprehensive policies that account for the environmental costs of growing nutrient pollution is not solely a result of knowledge gaps but also a product of these intricate socio-political mechanisms. Furthermore, while recent research and policy recommendations have advocated for a dietary transition towards millets and coarse grains, it is equally critical to examine and optimize existing practices of wheat and rice cultivation – staples with deep cultural roots in many parts of India[7,39,40].

Our study helps to fill this gap by quantifying the nutrient pollution embedded in the national agricultural system through the domestic food trade network. We focus on rice and wheat, two significant crops that contribute approximately 94.5% of the nutritional value compared to other cereals, despite India producing more than 217 different crops (see Supplementary Note and Supplementary Fig. 1)[32,41–43]. Our assessment tracks the flow of goods through the interstate rail network in the recent decade (2009–2020) and assesses environmental damage borne by the producer to meet consumer demand. We calculate the required cultivated area for traded crops and estimate the total application of fertilizers, considering nutrients from manure, atmospheric deposition, and biological nitrogen fixation[32]. Then, we explore the concept of NuUE to analyze virtual nutrients in interstate trade, using the surplus of nutrients as an indicator of environmental pollution[17,44]. Further, using a suite of well-established estimation approaches (see Method section), we provide quantitative estimates of nutrient losses such as atmospheric emission, leaching, and runoff and its equivalent graywater footprint[45]. In summary, the objectives of this study include understanding the spatiotemporal evolution of physical and virtual nutrient flow within India's interstate agricultural trade network, examining the environmental load on key production regions, assessing the sustainability of domestic wheat and rice trade systems in light of nutrient surplus, and providing policy recommendations for environmentally sustainable food security. This work offers an integrated examination of nutrient pollution within India's domestic trade network by mapping the network of producing and consuming regions and transposing nutrient surplus into an equivalent graywater footprint, providing a comprehensive understanding of the environmental implications. These insights could serve to inform policy decisions for central and state governments in the realms of agriculture and environmental management. Furthermore, regulatory and pricing authorities could leverage this data to restructure subsidies, incorporating credit-based systems for states that are pivotal in contributing to national food security[36–38]. The findings could offer a foundation for designing and exploring alternate trade network configurations that aim for environmental sustainability without compromising food security goals.

Results

First, we analyze subnational data sets for traded crops and estimates of cereal crop yield to understand the transfer of physical nutrients between states and the virtual surplus produced by cereal crops (Supplementary Table 1). We focus on the interstate rail trade, which accounts for 80% of the foodgrains movements in India (Supplementary Fig. 11)[46], tracing the flow of two key cereal crops (wheat and rice) and the macronutrients (N and P) involved (Fig. 2a, b; Supplementary Data 1 and Supplementary Fig. 1). Our network flow analysis reveals that for rice and wheat combined, Punjab and Haryana accounted for nearly 52% of total exports, which translates into a physical nutrient transfer of around 262 $\mathrm{GgNyr^{-1}}$ and 54 $\mathrm{GgPyr^{-1}}$ during the period 2009–2020 (Supplementary Fig. 2). The disaggregated analysis for rice and wheat further reveals that Punjab, Andhra Pradesh, Chhattisgarh and Haryana account for 79.5% of the rice trade, while Punjab, Haryana, and Uttar Pradesh account for 93.7% of the wheat trade (Fig. 2a, b). We note that while Chhattisgarh ranks 3rd in rice export (representing 17.2% of total export), it ranks 1st in terms of total applied N (around 22% of total applied N), which could be due to poor yield and therefore higher volumes of application of nutrients (Fig. 2c, e; Supplementary Data 1 and Supplementary Fig. 3). Although Haryana accounts for 22% of the total wheat trade, it represents 36% of the total applied N in the export network (Fig. 2d, f; Supplementary Data 1). The excessive use of N, P in crop production results in excessive aquatic losses (leaching and runoff, hereafter referred to as leaching), causing nutrient pollution that threatens both aquatic and human life[47]. To further highlight consumption hotspots, we found that Tamil Nadu (3.75 Mt), Maharashtra (3.61 Mt), Uttar Pradesh (2.76 Mt), Karnataka (2.61 Mt), West Bengal (2.39 Mt), and Bihar (2.18 Mt) generate the maximum demand, accounting for 62.4% of gross crop import. These, in turn, translate into the net nutrient application of 1140 $\mathrm{GgNyr^{-1}}$ and 330 $\mathrm{GgPyr^{-1}}$ to meet the import demand, which drives the nutrient surplus in the production regions (Figs. 2–4; Supplementary Data 2, Supplementary Data 3 and Supplementary Fig. 4).

Nutrient surplus, defined as the difference between the sum of total nutrient input (from all sources) and nutrient output (nutrient embedded in crops), is a key indicator of the potential agricultural nutrient lost in the environment[17]. Therefore, using the concept of NuUE (Nu_{output}/Nu_{input}), we calculate the surplus of N and P for wheat and rice, respectively (see Method section, Supplementary Fig. 5)[17,44,48]. For rice, the top four exporting states retain 79% and 78.4% of the total national surplus of N and P, respectively (Fig. 3a, c; Supplementary Fig. 4). Similarly, the four main exporting states retain 90.9% N and 91.9% P for wheat trade (Fig. 3b, d; Supplementary Fig. 4). From the importer's perspective, the four largest rice importers (Tamil Nadu, Karnataka, Maharashtra, and Bihar) were responsible for the 50.3% and 51.0% N and P burden, respectively, in the producing/exporting states. Similarly, the leading wheat importers states of West Bengal, Maharashtra, Uttar Pradesh, and Gujarat, represented 51.2% and 51% of the surplus N and P, respectively (Fig. 3e, f; Supplementary Fig. 6).

Next, we analyze the change in nutrient flow in the domestic trade network by quantifying the evolution of the nutrient surplus generated on the regional scale over the recent decade of

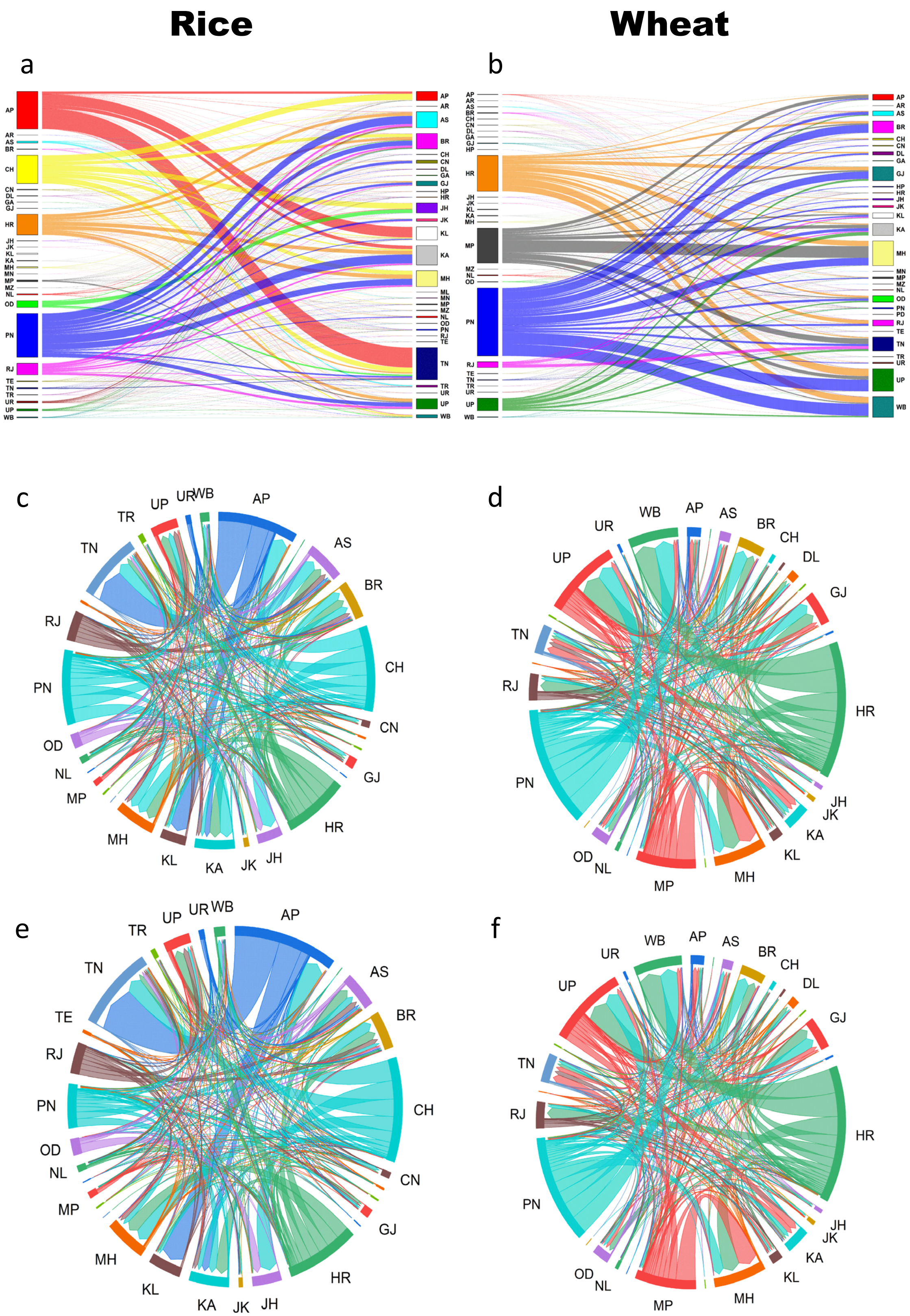

Fig. 2 Interstate trade of two primary crops, rice, and wheat, in India. a and **b** display the average exports of rice and wheat, respectively, through the interstate trade network. The links between states represent the flow of trade, and the width of the links indicates the volume of trade in quintals. Chord diagrams **c** and **e** provide information about the application of nitrogen (N) and phosphorus (P) specifically for the rice trade. On the other hand, **d** and **f** depict the application of nitrogen (N) and phosphorus (P) for the wheat trade. The colors of the links are based on the source region, with an arrow indicating the direction of trade towards the importing state. The width of the links represents the trade amount in Gigagrams per year ($Ggyr^{-1}$).

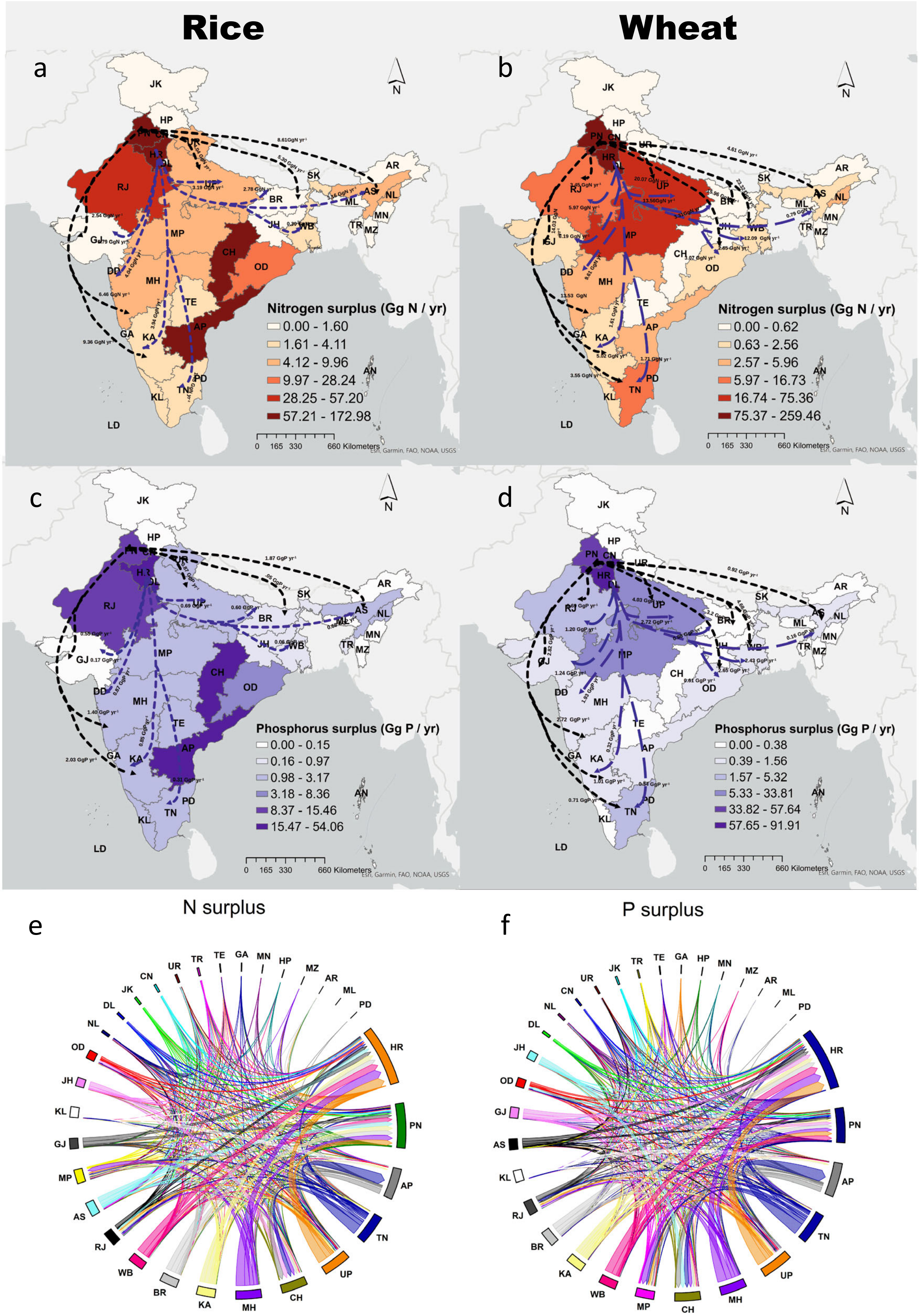

Fig. 3 Trade's contribution towards nutrient surplus. The spatial variation of nitrogen (N) and phosphorus (P) nutrient surplus in the interstate rice trade is shown in **a** and **c**, respectively. Similarly, **b** and **d** represent the spatial variation of N and P nutrient surplus in the wheat trade. Arrows in the figure depict the physical transfer of nutrients (N and P) from the two main production hubs to their respective import centers through trade. In the combined wheat and rice trade chord diagram, **e** and **f** establish connections between consumers and their respective nutrient surplus hubs for N and P, respectively. The colors of the links are based on the consumer state, and the width of the links indicates the surplus amount in (Ggyr^{-1}).

Table 1 Physical and virtual nutrient transfer from producers to consumers.

	States	Physical N (Gg/yr)	N Surplus (Gg/yr)	Physical P (Gg/yr)	P Surplus (Gg/yr)
Producers	HR	89.7	413.5	18.3	135.9
	PN	172.2	301.9	35.3	73.1
	CH	29.9	176.8	6.5	55.1
	AP	40.6	147.5	8.8	51.8
Consumers	MH	(65.1)	(167.3)	(13.3)	(53.6)
	TN	(59.0)	(185.5)	(12.4)	(63.5)
	UP	(56.6)	(135.2)	(10.7)	(42.8)
	KA	(41.9)	(124.8)	(87.7)	(35.6)

Physical and virtual/surplus nutrient values within parentheses represent the demand/burden caused.

2009–2020 (Supplementary Figs. 4 and 6). We evaluated the surplus of nutrients due to the cumulative trade of rice and wheat in which Punjab, Haryana, Chhattisgarh, and Andhra Pradesh were the main retainers (Table 1). Furthermore, we found that Tamil Nadu, Maharashtra, Uttar Pradesh, and Karnataka accounted for the introduction of 610 $GgNyr^{-1}$, 200 $GgPyr^{-1}$ nutrient load through interstate crop trading in producing states (Fig. 3e, f; Table 1). Interestingly, Punjab and Haryana accumulated a surplus of 710 $GgNyr^{-1}$ and 200 $GgPyr^{-1}$, which could have severe implications for atmospheric emissions and water quality in the region[11].

Subsequently, we translated trade-driven nutrient surplus in production hubs into equivalent estimates of macronutrient losses through atmospheric emission and aquatic loss (leaching) (Fig. 4a–f). Specifically, using the national-scale Integrated Model to Assess the Global Environment- Global Nutrient Model (IMAGE-GNM)[49], we derived the leach/runoff and emission coefficients of nitrogen and phosphorus. In the recent decade, the domestic wheat and rice trade has contributed to the introduction of 514.3 GgN of nitrous oxide (N_2O – long-lived greenhouse gas[50]) emissions in India at the producers' end. Specifically, our findings indicate that of the 42.8 $GgNyr^{-1}$ of N_2O emission, four leading producers sustain 73.1% of this emission load (Haryana: 28.3%, Punjab: 20.0%, Chhattisgarh: 12.4% and Andhra Pradesh: 12.3%) (Fig. 4g). In addition, to satisfy the demand for distant consumption, an additional burden of 11.3 $GgNyr^{-1}$ and 1.0 $GgPyr^{-1}$ is introduced into the water bodies, of which Punjab (20.2% N, 5.4% P), Haryana (21.4% N, 9.4% P), Chhattisgarh (27.9% N, 11.8% P) and Andhra Pradesh (9.4% N, 11.6% P) retained 3856 GgN, 257 TgP cumulatively over the recent decade (Fig. 4g, h). Our finding indicates that in the past decade, the main exporting states have suffered an additional burden of 11030 GgN and 3622 GgP residues (legacy) in the soil (Fig. 4g, h) that either gets recycled during plant growth[51] or contribute to future environmental degradation[52].

In the realm of assessing environmental consequences of residual nutrients, the concept of a 'graywater footprint' serves as a metric to express the amount of freshwater needed to dilute pollutants to maintain water quality within prescribed standards[9,27,53,54]. The metric provides insights into specific environmental harms such as the risk of algal blooms, hypoxic conditions in aquatic ecosystems, excessive N or P concentrations that could degrade soil and water quality, loss of aquatic life, and subsequently, degraded quality of life for users of affected water bodies. It is a useful approach for gauging the environmental impact of nutrient pollution. Specifically, the graywater footprint framework enables us to quantify the indirect water consumption attributable to the production of these key crops, thereby providing a holistic view of the environmental costs involved[54]. In terms of the scale of the units, the graywater footprint is typically measured in cubic meters per tonne of crop produced, which allows for a standardized and more precise understanding of each crop's environmental impact. Our evaluation indicates a graywater equivalent of 378.8 billion cubic meters per year (bcm yr^{-1}) (for N and P combined) for the two crops. The weight of this environmental impact predominantly falls on Haryana, Punjab, Chhattisgarh, and Andhra Pradesh, which collectively bear 73.2% of the total graywater footprint (Fig. 5a; Supplementary Data 4). For perspective, this footprint is a significant proportion of India's average annual renewable water resource (Precipitation (P)-Evapotranspiration (E))[55,56], which is estimated as 1798.25 bcm yr^{-1} (see Method section). Further, using the difference between precipitation and actual evapotranspiration as the indicator of net water availability in a given state, we observe an average negative water balance in the states of Punjab and Haryana and parts of Western Uttar Pradesh (Supplementary Fig. 7). Previous studies have shown that groundwater storage in northern India, where these states are located, has declined at a rate of 2 cm per year between 2002 and 2013[57,58]. Complicating matters further, these areas also contend with the impact of residual nutrients in the water. Under water stress conditions, these nutrients can concentrate, leading to severe water quality degradation. Over time, without intervention, this situation could lead to irreversible damage to the water systems. To further establish the credibility of our findings, we compared our findings with national water well data (Supplementary Fig. 8)[59,60]. Although both Punjab and Haryana fall under highly water-stressed regions, states like Chhattisgarh, which is not currently considered overstressed, may be gradually approaching a state of future water quality crisis in the absence of appropriate technological or policy interventions. Collectively, these issues - the negative P-E balance, the decline in groundwater storage, and nutrient contamination - amplify the water stress in these regions, thus highlighting the pressing need to address the environmental challenges faced by these regions.

Finally, we examine a "what-if" scenario in which individual states pursue self-sufficiency, aiming to meet consumption demands independently, without external imports (see Method section). In this setup, even states with lower crop yields per hectare would be forced to increase their cultivation area significantly to compensate for the resulting supply deficit in the absence of trade. This shift towards self-sufficiency has considerable environmental implications, leading to an additional burden of approximately 24322 GgN and 7720 GgP of nutrient surplus in India (Fig. 5b; Supplementary Data 4 and Supplementary Fig. 9) which would further translate into a graywater load of 18035 billion cubic meters (for N and P combined) for the two crops. These estimates highlight the magnitude of the hidden cost involved in such a scenario. Although our research accentuates the environmental challenges facing production centers due to the over-reliance on these centers in the national trade system, it is essential not to downplay trade networks' integral role in achieving broader agricultural sustainability. Viewing self-sufficiency as a blanket solution to pollution localization and concentration oversimplifies the complexity of the problem[61]. Therefore, we argue for a more refined approach, promoting optimized agricultural practices that recognize and incorporate these hidden costs. These costs, including environmental degradation, resource depletion, and the wider socioeconomic implications, must be taken into account in policy formulations.

Discussion

Nutrient pollution is a pivotal factor that both contributes to and results from agricultural imbalances and climatic inequalities[62,63].

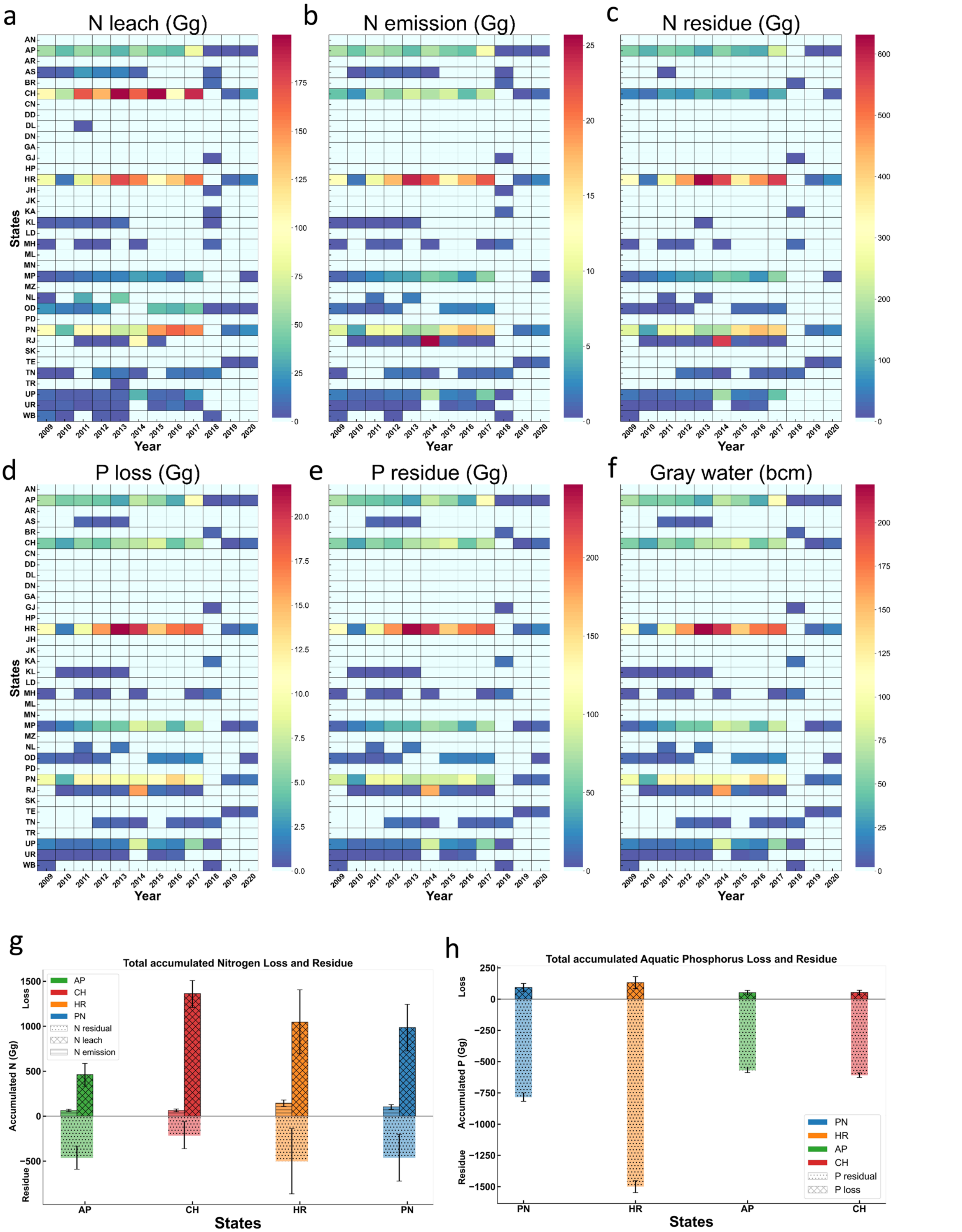

Fig. 4 Spatiotemporal evolution of nutrient loss and residue generated through interstate trade of wheat and rice from 2009 to 2020. a–e depict the heat maps illustrating the spatiotemporal evolution of nutrient loss and residue generated as a result of interstate trade in combined wheat and rice crops. Specifically, **a**–**c** present the heat maps for nitrogen (N) lost in aquatic systems, N emitted into the atmosphere, and N retained in the soil as residue (legacy), respectively. Meanwhile, **d** and **e** display the heat maps for phosphorus (P) lost in the aquatic system and P retained in the soil as residue (legacy), respectively. **f** provides an overview of the spatiotemporal evolution of accumulated graywater (N and P aggregated) generated through the combined trade of rice and wheat in India. **g** and **h** focus on the net cumulative N and P loss, as well as the residue accumulated due to the domestic trading of cereal crops in India's top four exporting states. Dotted patterns within the bars indicate residue accumulation, hashed patterns represent nutrient leaching, and lined patterns denote emissions. In figures **g** and **h**, the 95% bootstrap confidence intervals are shown as error bars centered at the mean.

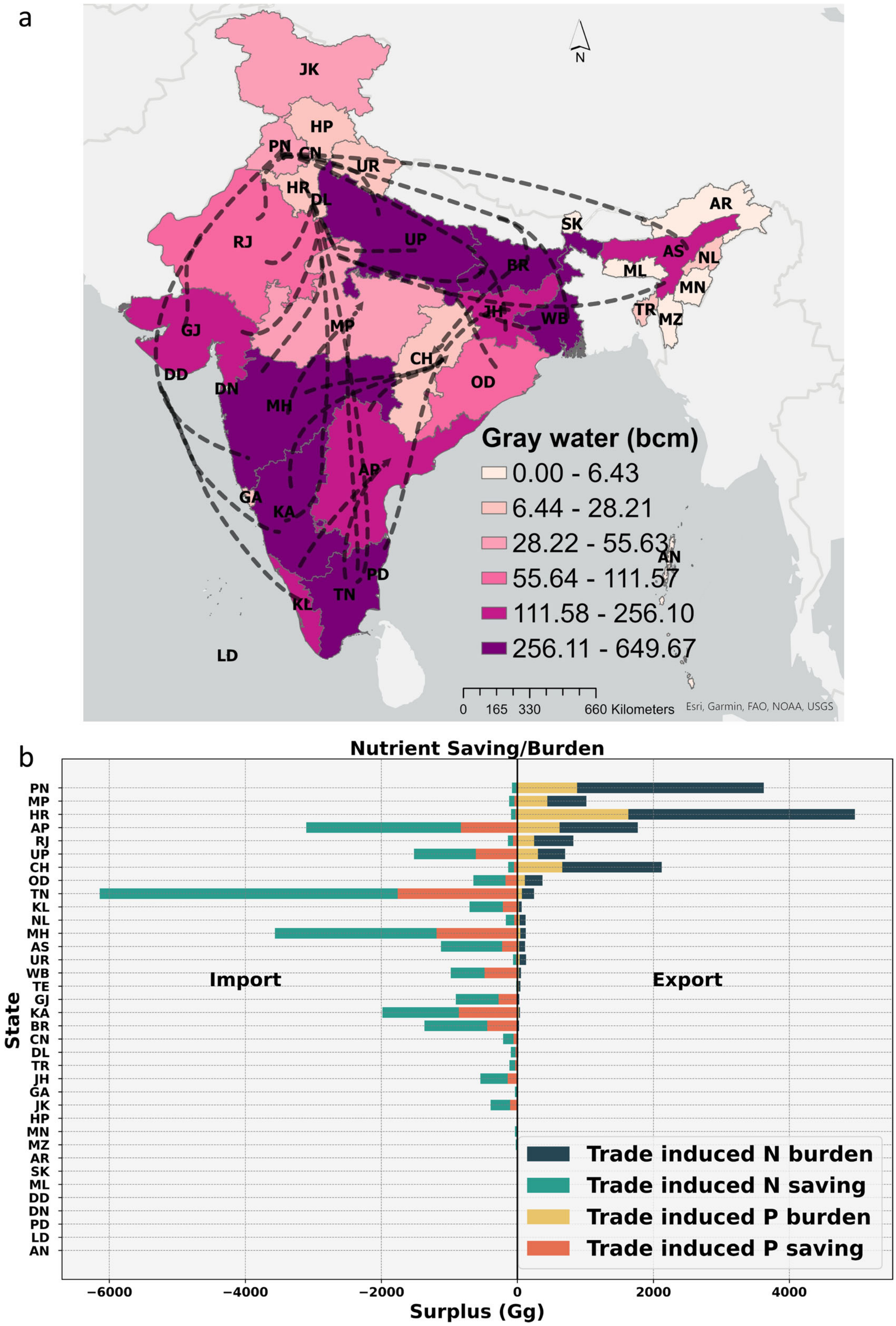

Fig. 5 Interstate Trade Effects on Graywater generation and Nutrient Savings. a Map illustrates consumption based on the graywater volume (bcm - billion cubic meters) that was not sustained by the importing state due to interstate trade of rice and wheat. The arrows connect states with the highest potential for graywater savings to their major exporters. **b** Bar graph represents hypothetical nutrient (N, P) savings that is achieved by importer states, contrasted with the actual nutrient burden sustained by production hubs over the course of the decade. The calculation of nutrient savings by importers is based on a hypothetical zero trade scenario.

Recognizing this, a shift to sustainable practices in both production and consumption is crucial to sustainably support a population nearing 10 billion while respecting the terrestrial planetary boundaries[64]. This acknowledgment underlines the urgency of examining the environmental impacts experienced by agriculture production hubs. Our study brings to the forefront the disparities in nutrient surplus generation between production hubs and importing regions within India as a result of interstate agricultural trade. By examining the trajectory of N and P exports (Supplementary Fig. 4), surplus, loss, and equivalent graywater (Fig. 4a–f), our work demonstrated how interstate trade of major cereal crops exacerbates the environmental consequences for the food bowls of India. Although food production driven by trade demands provides short-term financial benefits to exporting states, it has long-term environmental consequences[36,38]. This growing inequality in environmental burden has significant policy implications, particularly for the management of nutrient inputs and environmental sustainability at the production hubs. As such, the focus here is not solely on food sufficiency but on the urgent need to address these environmental disparities to achieve a more sustainable agricultural system. Our results advocate a pollution-informed restructuring of the trade network is needed to sustain the rising domestic food demand while reducing the state-level pollution pressure. The Green Revolution, first introduced in Punjab in 1960, made former Punjab (comprising present-day Punjab, Haryana, and Himachal Pradesh) a major agricultural production hub, with more than 70% of the country's food grain coming from the region[32]. However, the methods of fertilizer-intensive agricultural practices continue their legacy even decades later[52,65]. Although trade data present conservative estimates of macronutrients retained in producing states, it offers a glimpse of the growing disparity in nations' agricultural systems[66,67]. Although we focus on the national trade network for our analysis, environmental pressure on producing regions is observed throughout the world[16,17,47]. For example, the adverse effect of excessive fertilizer use has been reported in many regions of the United States of America and Europe[10]. Despite billions of dollars invested in reducing the consequences of agricultural pollution, inadequate improvement in water quality has been observed[52,65].

Interstate trade is necessary for states with poor agricultural production to meet their food demand. While a dense trade network decreases overall total fertilizer consumption, it unavoidably creates environmental instability at production regions (Figs. 3 and 5; Supplementary Fig. 9). With the enhancement of food production and population growth occurring at different rates in various geographic places, the present trade network must be strengthened to balance demand and supply[1]. If the leftover pollution is not considered, this will further worsen the situation of already polluted (production) regions. This study highlights such concerns and calls for a holistic approach, devising policies that consider leftover pollution generated due to intensive trading activities. Therefore, policies that aim to reduce nutrient pollution must address consumption issues more than previous treaties[4,16] and should strive to identify mechanisms to preserve the sustainable environmental status of the food bowls within and between nations without compromising national and global food security. Although researchers argue that with the advent of technological advances, comparable crop yield can be maintained while reducing pollution load, its translation to farm-level implementations remains a challenge[9,19,68]. Our analysis further promotes the need to adopt demand-side policies towards pollution reduction[9] and recommends better compartmentalization of nutrient pollution embedded in trade relationships for pollution reduction.

Maintaining a substantial NuUE helps to achieve multiple SDGs, as it is connected to both the environment and food security through SDG6 "Clean Water", SDG14 "Life Below Water" and SDG2 "Zero Hunger"[69]. This reconciliation of environment and food security may be addressed by domestic measures such as the improvement of agricultural NuUE and the changing demand (toward alternate cereal crops[7]), along with modifications in the domestic trade of agricultural products[20]. To improve the NuUE status through the effective use of fertilizer and agricultural practices and minimize environmental pollution, our study emphasizes policies that focus on redistributing funds from agricultural subsidies that aggravate environmental disparity to those that incentivize sustainable production[63]. There are additional opportunities for nations to support sustainable farming by implementing new sustainable technologies and practices, such as precision farming and plant breeding techniques, which would involve the support of the national government and thus greatly increase the efficiency of nutrient use[9,63]. The vexing question of who will pay for the environmental damage caused by trade-driven nutrient loss remains unanswered[4]. Our research contributes comprehensive data on the national flow of nutrients, outlining how pollution hotspots are intricately linked to consumption centers. The resulting imbalance leads to environmental degradation in production regions while also affecting agricultural sustainability in consumption areas. To address these challenges, our study emphasizes the importance of adapting existing policy mechanisms. For instance, introducing taxation schemes could help internalize the environmental costs, thereby encouraging responsible nutrient management[36,70]. Similarly, a credit-based system could promote better nutrient use by providing financial incentives for responsible (agriculture) practices[36]. Increasing the value of nitrogen fertilizers relative to their production cost could also serve as a deterrent against their overuse, assisting in the mitigation of nutrient imbalances, especially across key trading networks.

In light of the study's limitations and the assumptions upon which it is based, subsequent research could focus on several specific areas for refinement and extension. Enhanced granularity in the dataset to include diverse crop types and their corresponding transportation modes can be one priority. This would facilitate a deeper comprehension of nutrient trade dynamics. A second direction could involve developing dynamic models for atmospheric Nitrogen (N) deposition and P and N leaching and emission rates, providing an alternative to static or linear extrapolations[71]. Furthermore, comprehensive data repositories should also be developed to capture not just import but also re-export patterns for a fuller understanding of nutrient trade networks[28]. Lastly, the non-linear dependencies of nutrient cycles on hydroclimatic variables such as water content in soil, groundwater and rivers, along with varying temperature and rainfall intensity, necessitate complex modeling approaches, marking an important focal point for forthcoming investigations. An additional limitation to consider is the study's focus on N and P pollution solely within India's trade system. This omission of international trade factors could contribute to unaccounted-for environmental pressures, particularly in production hubs, thereby calling for a more detailed dataset that includes states serving as international trade hubs and the quantities involved.

Methods

Crop trade data preparation and pre-processing. We collected the trade data from the Directorate General of Commercial Intelligence, Statistics (DGCI&S), Government of India[72] for rice and wheat, the main sources of carbohydrates in India, which provides nutrition to billions of Indians (Supplementary Table 1)[7]. Trade data shows the transfer of rice and wheat between 28 states and eight union territories through the railway transport mode in India between 2009 and 2020. The data summarized the flow of import and export of the crops. We represent these data as a weighted directed network in which the link exists between two states where the trading took place. The weight is given from the exporting state i to the importing state j, with the amount of traded crops taken in quintals. We use crop area, production, and yield data from 2009–2020, collected from the Directorate of Economics and Statistics, Department of Agriculture and Farmers Welfare (DESAGRI) Agricultural Statistics at Glance reports[73]. The overall methodological framework is summarized in (Supplementary Fig. 5).

Nutrient input. We calculate the cultivated area required for traded crops to determine the fertilizer applied for crop production. The biophysical approach is widely used for crops and agricultural products to estimate the content of the crop footprint[14]. A similar approach is used as the ratio between the quantity of traded crops (kg) and the yields (kg ha^{-1}) to determine the cultivated area required for the traded crops (Eq. (1)).

$$A_{i,c,y} = \frac{T_{i,c,y}}{Y_{i,c,y}} \quad (1)$$

where the subscripts i, c, and y refer to the considered state, crop, and year, respectively. A, T, and Y represent the cultivated area, amount of crop traded, and yield, respectively.

Synthetic fertilizer and Manure application. This study focuses on the physical and virtual transfer of N and P nutrients in interstate traded crop grains. Information on N and P applied through fertilizers and manure varies with crop types and remains highly uncertain. Due to the unavailability of data at a finer spatial resolution, we performed the analysis using agricultural plot-level data of fertilizer and manure use intensities as input to represent these intensities in each state, which were taken from the Government of India's cost of cultivation surveys[74,75]. We used these plot-level data to calculate an average crop-specific fertilizer and manure application rate $p_{c,i,y}$ for crop c in state i across the years y (2009 through 2020), with the state-level input p (kg/ha) for crop c in year y calculated as (Eq. (2)).

$$p_{c,i,y} = \frac{\sum\left(C_{k,c,i,y} * p_{k,c,i,y}\right)}{\sum\left(C_{k,c,i,y}\right)} \quad (2)$$

where $p_{k,c,i,y}$ is the amount of input p in plot k, and C is the plot k cluster weight, a value provided within the Cost of Cultivation dataset to calculate representative values at the state level. This process was repeated for each input (synthetic fertilizer: Nu(SF) and manure applied: M) considered in the study[39,74].

The cost of cultivation survey data provides a historical record of crop-specific N and P fertilizer and manure consumption for various states by year. Although this data does not provide information for states with lower production value, to account for this, we use the reports of the International Fertilizer Association (IFA), which give the rate of application of crop-specific fertilization rate for disparate countries[43]. Total nutrients in manure applied to cropland were estimated using the N: P ratio in manure[17] multiplied by the N in manure applied to the soil[32]. While there remains uncertainty in the P: N ratio, we follow the past literature[44,48] and assume that the P: N ratio do not differ with the region, time, and treatment methods.

In addition to synthetic fertilizer and manure, biological fixation and atmosphere deposition contribute to the addition of nitrogen to the soil while producing crops.

Biological nitrogen fixation. Biological Nitrogen Fixation (BNF) is a vital nitrogen supply process in crop production and contributes significantly to the system budget for N. BNF is a natural process to transform atmospheric non-reactive nitrogen (N_2) into its reactive form, ammonia (NH_3). This process is carried out by prokaryotes, which reduce molecular nitrogen to ammonia and subsequently assimilate it into an amino acid. This study only considers the rate of N fixation on cropland taken from the Corporate Statistical Database of the Food and Agriculture Organization (FAOSTAT)[32].

Atmospheric deposition. In this study, the quantification of atmospheric N deposition (including dry and wet deposition of NH_x and NO_y) was obtained from atmospheric chemical transport models, using the data set of the National Center for Atmospheric Research (NCAR), the Chemistry-Climate Model Initiative (CCMI), which is part of the input datasets for Model Intercomparison Projects (input4MIPS)[76]. The data set is given in monthly time steps from 1850 to 2014 with a spatial resolution of 1.9 ° latitude by 2.5 ° longitude. We aggregated the data into a yearly time step. To obtain N deposition for cropland, we multiply the total N deposition by the proportion of the respective land area in each state. We assumed that the value of atmospheric deposition had not changed significantly since 2014. Further, we have not considered atmospheric P as it is not included in the IMAGE-GNM model[77].

Net nutrient input calculation. The net nutrient input rate is estimated based on an aggregation of the application rate of synthetic fertilizers, manure, biological fixation, and atmospheric deposition in the soil. To understand the spatial and temporal variability of the nutrient input with respect to N and P, we multiplied the application rate by the crop cultivated area in each state from 2009 to 2020 (Eq. (3)).

$$\begin{aligned} N &\Rightarrow Nu_{input(i,c,y)} = A_{i,c,y} * (Nu(SF)_{i,c,y} + M_{i,y} + BNF_{i,y} + AD_{i,y}) \\ P &\Rightarrow Nu_{input(i,c,y)} = A_{i,c,y} * (Nu(SF)_{i,c,y} + M_{i,y}) \end{aligned} \quad (3)$$

where $Nu_{input(i,\,c,\,y)}$ is the net nutrient input for N and P in (kg yr^{-1}). $Nu(SF)_{i,c,y}$ depicts the synthetic fertilization application rate (kg ha^{-1} yr^{-1}). $M_{i,y}$ corresponds to the manure application rate (kg ha^{-1} yr^{-1}). $BNF_{i,y}$ and $AD_{i,y}$ represent biological nitrogen fixation and atmospheric deposition rates, respectively.

Nutrient surplus estimation

Nutrient embedded in trade. To estimate the nutrient embedded in trade, we calculated the nutrient physically transferred through crops using data on trade volume and nutrient content. The uncertainty associated with the nutrient content data by crop type to estimate the nutrient yield and the data related to the same are limited in previous work[22]. Previous studies have assumed that nutrient content by crop type does not change with time and space scale since data by state and year are not available[48,78]. We also follow the same assumption while incorporating the nutrient content to estimate the nutrient embedded in trade transfer (Eq. (4)). We use the nutrient content provided in ref. [32] for the estimation of the embedded nutrients in the trade.

$$Nu_{output(i,c,y,x)} = T_{i,c,y,x} * Nu_{content(i,c,y,x)} \quad (4)$$

Where $Nu_{output(i,\,c,\,y,\,x)}$ is the nutrient output that also represents the nutrient embedded in the trade transfer. $P_{i,c,y,x}$ is the quantity of crops traded (kg), and $Nu_{content(i,\,c,\,y,\,x)}$ represents the nutrient content. Nu_{output} is only considered for the part of the traded crop (grain).

Nutrient surplus. In this study, we considered the concept of nutrient mass balance to estimate the nutrient surplus (Nu_{sur}) in the soil, which is the difference between Nu_{input} and Nu_{output}. Nu_{sur} includes nutrients that remain in the soil after crop production. A fraction of Nu_{sur} is recycled in the soil, whereas a considerable portion is lost to the environment, which can enter the atmosphere, surface water, and groundwater as N, P losses in various forms, including nitrous oxide in the air and the leaching of nitrate and phosphorus in the water[17,47]. Nutrient surplus serves as an indicator of environmental pollution. We use nutrient surplus as a proxy for virtual nutrient content, which is the amount of nutrient lost to the environment throughout the entire production process of a specific crop commodity[79]. A related term of Nutrient Use Efficiency (NuUE), the ratio of nutrient output to input is also a vital indicator for understanding agricultural efficiency in a given region[17,80]. Both terms are interconnected through their mathematical definitions (Supplementary Fig. 4, Eq. (5)).

$$NuUE_{(i,c,y,x)} = \frac{Nu_{output(i,c,y,x)}}{Nu_{input(i,c,y)}}$$
$$Nu_{sur(i,c,y,x)} = Nu_{output(i,c,y,x)} * \left(\frac{1}{NuUE_{(i,c,y,x)}} - 1\right) \quad (5)$$

Nutrient loss and residue. There are two ways to estimate the loss of nutrients in the environment: (1) by taking the assumption of nutrient loss as a fixed fraction of Nu_{input} or Nu_{sur}[17,48], and (2) from the dynamic soil model to estimate the annual change considering the disparate characteristics of the soil and the nutrient budget[44]. Nitrogen loss in terms of leaching/runoff (Eq. (7)) and N_2O - N emission (Eq. (6)) was derived using a dynamical model, the IMAGE-GNM model (see Supplementary Methods and ref. [49]), along with uncertainty bounds derived from assumptions made about the choice of parameters. To calculate the loss of P in the form of runoff/leaching losses (aquatic loss) (Eq. (7)) we used the coefficient derived from IMAGE-GNM and the spatially explicit dynamic phosphorus simulator (DSPP) model from ref. [44]. We assumed that the P and N loss rate is the same for all types of crops within the country/state throughout the year.

$$[N_2O - N]_{(i,y)} = (Nu(SF)_{i,y}) * E_{f1} \quad (6)$$

where, N_2O-N is the annual amount of N_2O - N emissions from the surplus of N (kg yr^{-1}) in the managed soil. E_{f1} represents the emission factor for N_2O emission from $N_{surplus}$ which were derived using IMAGE-GNM model.

$$N \Rightarrow [N_{(L)}]_{(i,y)} = (N(sur)) * L_f$$
$$P \Rightarrow [P_{(L)}]_{(i,y)} = (P(input)) * L_f \quad (7)$$

Where $N_{(L)}$ and $P_{(L)}$ are the annual amount of aquatic loss of N and P through leaching and runoff, respectively. L_f is the coefficient representing the fraction of all surplus/input N and P (kg yr^{-1}) in managed soils that are lost by leaching and runoff. These aquatic loss coefficients were calculated using spatially explicit IMAGE-GNM[49] and dynamic phosphorus simulator (DSPP) model from ref. [44].

$N_{residue}$ is estimated based on the N that remains in the soil after being lost through emission, leaching, and runoff. For phosphorus, P loss has been assumed as a fraction of P in input or surplus[44]. We divided P_{input} into $P_{residue}$ that remains in the soil after P_{loss} (Eq. (7)) and P_{output}. Estimating P_{loss} is challenging as it requires complex biogeochemical models to estimate $P_{residue}$. However, these models give a large uncertainty at the national scale[44]. Here, we employ the same approach followed for N_{loss}, where the fraction of P_{input} is considered for P_{loss}. We estimate that P_{loss} through leaching and runoff for India is 7.1% of the P_{input} for P, taken from IMAGE-GNM[44,48]. We assume that the loss rate of P is the same for all types of crops within the country throughout the year and varies between 7.1%[44] and 12.5%[81] of P_{input} globally. To offer an understanding of the relative magnitudes of uncertainties associated with our modeled outputs, we undertook a two-pronged approach. Supplementary Fig. 10 elucidates the relative scales of uncertainties within and across the values derived using the tier-1 methodological framework of the Intergovernmental Panel on Climate Change (IPCC)[45,49,78,81] and IMAGE-GNM models, thereby offering a comparison of modeled N components. Secondly, we employed the Monte Carlo simulation approach, running 1000 iterations to quantify the uncertainties inherent to the IPCC methodological framework. In these simulations, parameter values associated with different N components (e.g., leaching fractions, NO_2 losses) were sampled with replacement within the bounds specified by the IPCC guidelines (See Supplementary Methods for more details).

Graywater estimation. After nutrient addition through leaching from the interstate trade of rice and wheat, we used the concept of graywater to understand the amount of water required to dilute existing water storage to maintain the permissible quality of water in surface and subsurface water bodies. Here, we use 45 mg/l[82] nitrate as the permissible limit for dilution and 0.1 mg/l for phosphorus leaching[23]. We follow a similar approach to estimate graywater as outlined in refs. [9,54]. To validate our findings, we use the national water well data from the Central Water Commission, an agency providing detailed data on water quality parameters, including nitrate levels, across India. The analysis with this data shows similar patterns of water quality degradation in the Northern regions of India where we report high nitrate leaching in our study (Supplementary Fig. 8)[59,60].

Freshwater availability. The quantity of available freshwater is typically calculated as the difference between precipitation (P) and evapotranspiration (E), a measure commonly used to indicate the availability of "freshwater" in hydrology[55,56]. For our study, we sourced daily precipitation data from the India Meteorological Department (IMD)[83] and evapotranspiration data from the latest iteration (v3.6a) of the Global Land Evaporation Amsterdam Model (GLEAM)[84]. To calculate grid-wise and national averages in terms of billion cubic meters per year (bcm/yr), we start by determining the daily P-E values for each grid cell using the sourced data. These daily P-E values are then aggregated over the year to provide annual P-E values for each grid cell. Subsequently, these annual P-E values are converted into volume using the latitude-dependent area of the respective grid cells. This calculation provides us with the annual volume of available freshwater for each cell. Finally, these volumes are summed across all grid cells to yield the total annual volume of available freshwater for the entire country, thus giving us the national average in units of bcm/yr.

Nutrient savings. We use the concept of nutrient savings[80] based on the trade of a nutrient x from an exporting state j to an importation state i for y crop (Eq. (8); Supplementary Fig. 9).

$$NuS_{i,j,y,x} = T(i,j,x,y) * Nu_{sur(i,x,y)} - T(j,i,x,y) * Nu_{sur(j,x,y)}$$
$$= HNu_{sur(i,y,x)} - T(j,i,x,y) * Nu_{sur(j,y,x)} \quad (8)$$

where T is the export of the product y from region j to i. $Nu_{sur(j)}$ represents the amount of nutrient surplus generated for the production of a unit of crop y. $HNu_{sur(i,y,x)}$ represents a hypothetical nutrient surplus generated in state i to produce the imported crop volume, assuming that no virtual nutrient inflows from state j are happening (no trade scenario). For this hypothetical what-if scenario, state i would have to apply the required nutrient for crop production entirely based on their own yield and fertilizer application rate to produce T amount of product y, i, j and x correspond to the importing state, the exporting state, and the type of nutrient (N, P), respectively (Eq. (9)).

$$NuS_x = \sum_{i,j} NuS_{i,j,y,x} \quad (9)$$

We computed the net savings for all trade relationships and aggregated the NuS for all states.

Although our study used state-of-the-art methods in this field[14,16,17,44], several additional aspects of nutrient budgeting along with food security and sustainability can be analyzed. Given limitations in data availability and resolution, our study is founded on several assumptions. These assumptions include: (a) uniform nutrient content by crop type over various time and space scales, following FAO soil nutrient budget guidelines[32]; (b) linear static value of atmospheric Nitrogen (N) deposition rates obtained from input4MIPs data for the period of 2016 up to 2020[76]; (c) temporally constant but spatially variable leaching rates for Nitrogen and Phosphorus, as informed by the IMAGE-GNM model[45,49], detailed discussions on these uncertainties involved in the modeling approaches employed (e.g., IMAGE-GNM and IPCC) have been discussed elsewhere[49,81,85]; and (d) the use of Nitrogen surplus rather than total nitrogen input for nutrient loss calculations, based on its acknowledged role as a reliable proxy for environmental loss in existing research[71]. An additional assumption concerns the flow of agricultural products: some key importing states in India are also exporters of other significant crops, sometimes to the same production hubs or international markets. Additionally, importing states may further re-export finished agricultural products, indicating the need for the availability of more comprehensive data repositories for a fuller understanding of the issue. Despite these assumptions, the primary findings of our study align with current literature and policy dialogs that point to environmental challenges in major production areas[10,13,19,47]. Our work aims to provide a quantitative basis for understanding these challenges.

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

Data availability

Trade data sets used in this study are obtained from the Ministry of Commerce and Industry[72]. We used crop yield data for 2009–2020, collected from the Directorate of Economics and Statistics, Department of Agriculture and Farmers Welfare (DESAGRI)[73]. The intensities of fertilizer and manure use for each state were taken from the Government of India's cost of cultivation surveys (Supplementary Table 1)[74,75]. Nutrient budgeting was performed on Microsoft Excel, OriginPro Learning Edition, and Python was used in figure generation. The processed data is available at our GitHub repository: https://github.com/shekharsg/Interstate-Agro-Trade-Pollution-in-India-.git.

Code availability

The analysis is performed using the standard python packages. The code is available at our GitHub repository: https://github.com/shekharsg/Interstate-Agro-Trade-Pollution-in-India-.git.

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Author contributions

S.S.G., R.D., R.K. and U.B. designed the experiments. S.S.G. and R.D. performed the analysis. S.S.G., R.D., R.K. and U.B. wrote the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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