The nitrogen footprints of China’s major urban agglomerations: understanding regional challenges to advance sustainable development

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Abstract
The overgrowth of reactive nitrogen emissions (Nr, all species of nitrogen except N2 gas) is a major cause of environmental pollution, especially in rapidly urbanizing regions. The nitrogen footprint (NF) indicator has been widely used to assess Nr losses occurring from the consumption of food and energy. We undertake the first attempt to apply NF methods to explore the spatial-temporal NF characteristics of major urban agglomerations in China between 2000 and 2019, and find that the highest level of annual NF (average 3868 Gg N yr\(^{-1}\)) was produced by the Yangtze River Delta urban agglomeration (YRDUA), followed by the Beijing–Tianjin–Hebei urban agglomeration (BTHUA) (average 2657 Gg N yr\(^{-1}\)). Their NF growth rates showed similar downward trends during the study period, while the Pearl River Delta urban agglomeration (PRDUA) (average 1528 Gg N yr\(^{-1}\)) retained a higher growth rate. The average proportions of food NF (FNF) in BTHUA, YRDUA and PRDUA were 57.64%, 68.64% and 66.79%, respectively. Compared to the FNF, the energy NF gradually plays a more important role in China’s urban agglomerations compared to other countries. Analysis of the underlying drivers showed that an increasing urbanization rate boosted the NF of YRDUA, and rising GDP per capita significantly contributed to the NF growths of BTHUA and PRDUA. Through scenario analysis, we found that shifting to healthy dietary patterns and a partial substitution of fossil fuels with clean energy, as well as improvements in rural wastewater treatment, could contribute to NF reductions by 2030. The largest potential NF reduction is predicted in PRDUA (29% reduction), followed by YRDUA (23% reduction) and BTHUA (18% reduction). The energy reduction scenario is considered to be the most realistic in reducing the NF. We demonstrate the potential of the NF as a tool for the assessment of sustainable development in urban agglomeration, which may prove instructive for broader research on sustainable Nr management.

1. Introduction
Nitrogen (N) is an essential element for terrestrial ecosystem functions and processes, but improper N utilization by humans through agricultural and industrial production to meet the demands of increasing population, have significantly contributed to the growth of reactive nitrogen (Nr; all species of N other than N\(_2\) gas), which has mostly been released into the global environment, leading to a ‘Nitrogen Cascade’ that has been difficult to control (Vitousek et al 1997, Galloway et al 2003, Sutton et al 2011). Unlike the natural N cycle, this anthropogenically modified N cycle could cause Nr to become a major factor for the occurrences of multiple environmental pollution in sequence (e.g. smog, acid rain formation, water eutrophication, soil acidification and global warming), which have negative impacts on human health and the biosphere (Galloway et al 2003, Shibata et al 2017). This makes the accurate
assessments of Nr emissions from human activities an urgent priority, especially if we wish to sustainably reduce Nr (Gu et al. 2019) and keep countries and the world within ‘planetary boundaries’, which are defined as the safe operating space for humanity based on the intrinsic biogeochemical processes supporting Earth’s stability (Steffen et al. 2015).

The importance of sustainable Nr management was primarily highlighted in the ‘Nanjing Declaration’ issued by the 2004 International Nitrogen Initiative (INI 2004) Conference held in China, which affirmed the necessity of global Nr reduction by confronting soaring food and energy consumption (Erisman 2004). Additionally, the INI 2016 Conference held in Australia stated that the cascading environmental effects of Nr should be minimized by reducing Nr losses from food production and energy combustion by optimizing Nr management for farmers, energy providers and consumers. The goal to minimize Nr is closely related to the United Nations Sustainable Development Goals (SDGs) involved with N utilization (Wiedmann and Lenzen 2018, Gu et al. 2019, Morseletto 2019): Goal 2 (zero hunger, improve nutrition and promote sustainable agriculture for food security), Goal 3 (good health and well-being, ensure nutrition for health, demand for human well-being), Goal 6 (clean water and sanitation, ensure clean water without pollution pollution for all), Goal 12 (responsible consumption and production, ensure anthropogenic consumption and production without excessive pollutant emissions), and Goal 14 (life below water, minimize the impacts of ocean acidification on marine and coastal ecosystem). Estimated damages to human health and the environment caused by N pollution, were estimated to cost 70–320 billion Euro (78.50–358.85 billion USD) per year in the European Union (Sutton et al. 2011). Between 2004 and 2014, the annual cost of N pollution in China was 680–740 billion RMB (106.49–115.88 billion USD) and rates of urbanization increased from 42% to 55% (Xian et al. 2019), posing major challenges for China’s national ambition to achieve the abovementioned SDGs by 2030 (Gao et al. 2021). China continues to prioritize urbanization, particularly in the low-income inland and western regions, as its economic growth ‘catches up’ with advanced, developed economies. As a result of its economic priorities, China’s urbanization levels could reach 75% by 2030, with major cities, on average, accommodating over 1 billion people (Bai et al. 2014, Fang et al. 2019).

Urban agglomerations can be defined as an integrated group of cities sharing common interest and fate. These cities generally form the strategic cores of national economic development, acting as engines of industrialization and regional and international connectivity. In China, urban agglomerations are therefore critical foci of sustainable development (Fang and Yu 2017). In particular, increasing urbanization boosts Nr production and release, and China has already become the largest anthropogenic Nr source in the world (Cui et al. 2013, Shi et al. 2015).

The INI 2016 Conference addressed the need to raise conscious awareness of the nitrogen footprint (NF) (Gu et al. 2019). The concept of NF was proposed at the INI 2010 conference, and was developed after the conceptualization of ecological, carbon, and water footprints, which have since been widely applied as effective indicators to guide reductions in negative human impacts on the environment (Leach et al. 2012, Pierer et al. 2014, Shibata et al. 2017). The NF was defined as the total amount of Nr released into the environment as a result of individual or collective resource consumption, and expressed in total units of N atomic weight, which can be estimated through the online platform of the N-Calculator model (www.n-print.org) (Leach et al. 2012). This approach to NF estimation has been widely adopted to link anthropogenic resource consumption with environmental impacts in several counties, including Austria (Pierer et al. 2014), Germany (Stevens et al. 2014), the Netherlands (Leach et al. 2012) and the United Kingdom (Stevens et al. 2014) in Europe, as well as China (Cui et al. 2016, Guo et al. 2017), Japan (Shibata et al. 2014), India (Dhar et al. 2021), Egypt (Elrys et al. 2019), Tanzania (Hutton et al. 2017), Australia (Liang et al. 2016), Canada (McCourt and MacDonald 2021) and the United States of America (Leach et al. 2012) in other continents. In China, several recent case studies at different scales were conducted, including at the provincial (Xian et al. 2021), the watershed (Zeng et al. 2019), and urban landscape level (Xian and Ouyang 2016, Xia et al. 2020). Most of studies adopted the population-based weighted average approach of the N-Calculator method for bottom-up NF calculations and found that the cities concentrated by urban population play a key role in regional Nr emissions in terms of their interactions with food and energy consumption, underscoring the urgency of reducing Nr losses from the perspective of urban agglomeration.

Previous studies found a prominent lack of coordination between urbanization and environmental protection for urban agglomerations (Fang et al. 2019), which are the main sources of regional N pollution in China (Dong and Xu 2019, Wei et al. 2019). However, the aforementioned studies only focus on countries and provinces with sufficient data availability, or otherwise concentrated on a single city, inevitably neglecting the critical interactions between cities. Therefore, in this study we aim to demonstrate the application of a regional NF approach to articulate urban NF calculations, and assess the potential for Nr reduction through coordinated urbanization among cities We first assess the spatio-temporal characteristics of the urban NFs within three main urban agglomerations in China, and then determine how they contribute...
differently to Nr pollution through their driving factors. Furthermore, we project urban agglomeration NFs under different development scenarios (healthy diet, cleaner energy, waste treatment, etc) and finally assess potential NF reductions to identify key points where policy interventions can effectively mitigate regional Nr pollution towards sustainable development.

2. Materials and methods

2.1. Study area

Three representative and economically vital national-level urban agglomerations in China, which have been sites of rapid urbanization in recent decades (Zhou et al 2021), were chosen as case studies (figure 1). The agglomerations chosen include the Beijing–Tianjin–Hebei urban agglomeration (BTHUA) (between 36°07’ and 42°65’ N, 113°46’–119°79’ E), the Yangtze River Delta urban agglomeration (YRDUA) (between 27°10’ and 35°10’ N, 114°50’ and 122°30’ E) and the Pearl River Delta urban agglomeration (PRDUA) (between 21°32’ and 24°25’ N, 111°22’ and 115°22’ E). BTHUA includes the capital city of Beijing and Tianjin municipality, as well as all 11 prefecture-cities from neighboring Hebei province. Exponential population growth in this region has accelerated the demand for natural resources and has led to associated environmental impacts (Fang et al 2019), especially in Beijing, which makes rapid urbanization and sustainable resource consumption difficult. The primary goal of establishing a policy mechanism to integrate BTHUA is to solve Beijing’s ‘big city diseases’ by transferring its non-capital functions to surrounding areas and at the same time to support the economic development of other cities in this urban agglomeration. As the largest of the three urban agglomerations (Yu et al 2020), YRDUA has the most prosperous economy. It is supported by the strongest innovation ability in China, encompassing 26 cities across several provinces, including Shanghai municipality, nine prefecture-cities in Jiangsu Province, eight prefecture-cities in Zhejiang Province, and eight prefecture-cities in Anhui Province. During 1980–2015, the land cover ratio of built-up area in YRDUA increased from 4.1% to 24.8%, with rapid urbanization (Zhou et al 2021). Finally, PRDUA, located in the central part of the Guangdong province in Southern China, has achieved the highest urbanization in China, becoming the largest urban area by land mass in the world (Zhou et al 2021). The PRDUA urban agglomeration has nine prefecture-cities. In this study, the entire urban agglomeration was divided into NF assessment units based on the administrative boundaries of cities and the socioeconomic characteristics of the cities embodied in the urban agglomerations are showed in table S1 (available online at stacks.iop.org/ERL/17/045020/mmedia).

2.2. NF calculation

2.2.1. Food NF (FNF)

The FNF is a main component of NF, capturing all of the Nr losses along the chain of food production and consumption. Previous studies have shown that it can account for more than 68% of national NFs (Leach et al 2012, Shibata et al 2014, Stevens et al 2014, Cui et al 2016). The N-Calculator algorithm (Leach et al 2012) was applied to calculate FNF in this study, which assumed that all N consumed by people was finally released into the environment as human waste. Unlike previous case studies in China (Zeng et al 2019, Xia et al 2020), the Nr removal rate was considered in FNF calculation here, since secondary sewage treatment plants are widely available in these urban agglomerations with higher urbanization rates (URs). Additionally, the Nr loss associated with energy consumption during food production and consumption was considered in energy NF (ENF) accounting, so it was excluded from FNF calculations. The main food types considered in this study included vegetarian foods (e.g. cereal, legume and vegetable), animal foods (e.g. pork, beef, mutton, poultry and seafood), and non-staple foods (e.g. eggs, dairy, fruits, sugar and edible oil). The total personal FNF was the sum of NF resulting from the above selected types of food consumption from 2000 to 2019, and the FNF of a city in a specific year can be calculated by the following equations:

\[ \text{FNF}_c = \text{FNF}_c^{\text{FD}} + \text{FNF}_c^{\text{VNF}}. \]  

(1)

\[ \text{FNF}_c^{\text{FD}} = \sum_{i=1}^{n} \text{FD}_i^{\text{FD}} \times N_i \times (1 - \text{RV}_i^{\text{FD}}) \times P_c^{\text{FD}} + \sum_{i=1}^{n} \text{FD}_i^{\text{FD}} \times N_i \times \text{VNF}_i \times P_c^{\text{FD}}. \]  

(2)

\[ \text{FNF}_c^{\text{VNF}} = \sum_{i=1}^{n} \text{FD}_i^{\text{VNF}} \times N_i \times (1 - \text{RV}_i^{\text{VNF}}) \times P_c^{\text{VNF}} + \sum_{i=1}^{n} \text{FD}_i^{\text{VNF}} \times N_i \times \text{VNF}_i \times P_c^{\text{VNF}}. \]  

(3)

\[ \text{VNF}_i = \frac{\text{Nr}_{\text{loss}}}{\text{Nr}_{\text{con}}}, \]  

(4)

where FNF\(_c^{\text{FD}}\) represents the food NF of city \(c\) in a specific year \(t\), FNF\(_c^{\text{FD}}\) and FNF\(_c^{\text{VNF}}\) are the food NFs of urban and rural residents in the city, respectively. \(i\) represents the different types of food (\(n = 13\)) with \(N_i\) meaning the N content of food \(i\), the values of which are taken from a previous study of national NF accounting (Cui et al 2016). FD\(_i^{\text{FD}}\) and FD\(_i^{\text{VNF}}\) represent the amounts of food \(i\) consumed by urban and rural residents per capita, and the values for prefecture-cities are retrieved from provincial residential food consumption data, due to the lack of city-level statistics. P\(_c^{\text{FD}}\) and P\(_c^{\text{VNF}}\) respectively represent the populations.
of urban and rural residents in city \( c \). \( RV_u^c \) and \( RV_r^c \) indicate sewage treatment rates for urban (75%) and rural (6%) areas (Guo et al. 2017). \( VNF_i \) is the virtual N factor of food \( i \), indicating the amount of \( N \) loss per unit \( N_{\text{con}} \) (N content) in food products consumed by residents (Leach et al. 2012). The values of \( VNF_i \) are different depending on the specific food item studied, and are based on previous research on regional NF estimations in China (Guo et al. 2017). The \( VNF_i \), \( RV_u^c \) and \( RV_r^c \) of cities are assumed to be constants during 2000–2019, since there is no available data on their temporal changes (Cui et al. 2016, Guo et al. 2017, Zeng et al. 2019).

### 2.2.2. ENF

The ENF mainly refers to \( NO_x \) emissions resulting from fossil fuel combustion for economic production and residential livelihoods, including agriculture, industry, transportation, commerce and housing, among others. This part of the NF can be calculated using top-down and bottom-up approaches (Cui et al. 2016, Zeng et al. 2019). Given that the statistics of urban and rural per capita energy consumption are scare for most prefecture-level cities in China, the top-down method was adopted to calculate ENF by aggregating the total energy consumed within a city and the emission factors for different energy sources. The ENF can be calculated as follows:

\[
ENF_t^c = \sum_{j=1}^{m} \left( Q_j \times \frac{EC_c}{EC_p} \times EF_j \right),
\]

where \( ENF_t^c \) represents the energy NF of city \( c \) in a specific year \( t \), \( j \) represents the main energy combustion, including coal, petroleum, diesel and natural gas. \( Q_j \) represents the amount of energy \( j \) consumption in the province where city \( c \) is located. \( EC_c \) and \( EC_p \) are the total electricity consumption of city \( c \) and the whole province, respectively. Despite the shortage of long-term statistics about urban and rural energy consumptions in prefecture-level cities, the amount of energy \( j \) consumed in city \( c \) can be estimated based on the ratios of \( EC_c \) to \( EC_p \), because coal is the dominant energy for cities’ fuel consumption, which is mainly burned for producing electricity. Additionally, data on cities liquefied petroleum gas use is lacking, so this energy consumption is not included in our ENF calculations. \( EF_j \) is the emission factor of \( NO_x \) classified by coal (3.0 g N kg\(^{-1}\)), petroleum (7.4 g N kg\(^{-1}\)), diesel (16.5 g N kg\(^{-1}\)) and natural gas (1.2 g N m\(^{-3}\)) (Xian et al. 2016).

### 2.2.3. Urban agglomeration NF

The NF of the specific urban agglomeration can be calculated by summing up the NF of constituent cities as follows:

\[
UANF_t^x = \sum_{c=1}^{z} (FNF_t^c + ENF_t^c),
\]

where \( UANF_t^x \) represents the NF of urban agglomeration \( x \) in a specific year \( t \), \( z \) represents the number of
cities in the urban agglomeration $x$. The $z$-value was 13 for BTHUA, 26 for YRDUA and 9 for PRDUA.

2.3. Exploring the correlation between NF and socioeconomic indicators

URs and GDP per capita are generally understood to be the major factors influencing national NF dynamics (Cui et al 2016, Xian et al 2019). First, to investigate the socio-economic factors affecting the sustainable development of urban agglomeration in terms of NF from 2000 to 2019, a regression analysis was conducted:

$$UANF_x = a_0 + bF_x,$$

where $a_0$ and $b$ are the intercept and coefficient. $F_x$ represents the individual socio-economic variables concerning population urbanization, including UR, the proportion of people employed in primary industry (PP), the proportion of people employed in secondary industry (PS), and the proportion of people employed in tertiary industry (PT), as well as the factors concerning economic urbanization including GDP per capita, the percentage of GDP by primary industry (PGDP), the percentage of GDP by secondary industry (SGDP), and the percentage of GDP by tertiary industry (TGDP). Statistically significant differences ($p < 0.1$) indicate that the selected socio-economic factors explained the variations of urban NF to some extent in the studied urban agglomeration. Then, multiple linear regression tests, including eligible factors, was conducted to determine which socio-economic factor was the main driving force of variation of urban agglomeration NF, using the formula

$$UANF_x = a + b_1F_{1x} + b_2F_{2x} + b_3F_{3x} + b_4F_{4x} + b_5F_{5x} + b_6F_{6x} + b_7F_{7x} + b_8F_{8x} + \varepsilon,$$

where $a$ is intercept and $b_1, b_2, \ldots, b_8$ are coefficients. $\varepsilon$ is the error term. The aforementioned socioeconomic data used in this paper were mainly obtained from national and regional statistics from 2001 to 2020 (see supplementary information text S1 for more detail).

2.4. Scenarios and projections

China is committed to promoting urbanization for economic development, which contributes to reducing regional income disparities (Bai et al 2014). However, the launch of the ‘National Population Development Program (2016–2030)’ (SCC 2020a) proposed that the development of large, medium and small cities should be coordinated, and that the population growth of the ‘megacities’ (cities with a population in excess of 10 million people) within BTHUA, YRDUA and PRDUA should be limited. Therefore, using the total population and the NFs (2019) of the urban agglomerations as a baseline, a scenario analysis was applied to forecast how NF is expected to change by 2030 based on current population, and to assess the potential strategies for mitigating NF growth. These scenarios associated with NF changing are designed as follows:

(a) The projection with no actions to reduce cities’ NF, in the process with the UR reaching 75% by 2030 (Fang et al 2019), is the Business as Usual scenario.

(b) The projection with actions to mitigate the FNF through dietary shifts to the recommended dietary patterns suggested by the Chinese Dietary Guidelines (CNS 2021), with the ‘N-friendly meat’ poultry as the major meat consumption (Xian et al 2021), is the Healthy Diet scenario.

(c) The projection with actions to reduce the FNF by widespread improvements in the treatment rate of rural wastewater — increasing to 50% by 2030 — is the Rural Treatment scenario.

(d) The projection with actions to reduce the ENF to achieve low-carbon development (25% of total fuel energy will be replaced by non-fossil fuels by 2030) (SCC 2020b), is the Energy Friendly scenario.

(e) The projection with all of the above actions towards a total NF reduction is the Multiple Measures scenario.

3. Results and discussion

3.1. Temporal and spatial characteristics of urban agglomeration NFs

We observed that the NF dynamics of cities within the three urban agglomerations presented significant heterogeneity (figure 2). Shanghai had the highest level of NF (average 615 Gg N yr$^{-1}$) during 2000–2019 with a growth by of 91%. Beijing had the highest level of NF (average 401 Gg N yr$^{-1}$), Tianjin (average 394 Gg N yr$^{-1}$), Shanghai (average 352 Gg N yr$^{-1}$), Suzhou (average 325 Gg N yr$^{-1}$), Guangzhou (average 335 Gg N yr$^{-1}$) and Shenzhen (average 294 Gg N yr$^{-1}$) were also characterized as main NF producers experiencing annual NF (>400 Gg N yr$^{-1}$) in some years, or even the whole study period, and the NF of these cities increased by 69%, 101%, 185%, 156% and 221%, respectively. Meanwhile, 30% cities showed lower levels of NF (<100 Gg N yr$^{-1}$) (see supplementary information text S2 for more detail).

At the regional level, YRDUA, which is comprised of more cities than the BTHUA and PRDUA combined, produced the highest NF (average 868 Gg N yr$^{-1}$) among the urban agglomerations, followed by BTHUA (average 2657 Gg N yr$^{-1}$). Their regional NFs maintained rising trends and doubled by 2019 and their staged NF growth rates showed similar downtrends during the study period. Compared with the other two, PRDUA produced a lower regional NF (average 1528 Gg N yr$^{-1}$). However, it retained higher growth rates and the rate during 2015–2019 was even higher than during 2010–2015. By 2019, the regional NF of PRDUA increased by
The dynamics of the NFs of cities within urban agglomerations and the staged NF growth rates of the three major urban agglomerations from 2000 to 2019.

152%, aggravating regional N pollutions (Dong and Xu 2019).

The spatial distribution of NF growths in the urban agglomerations (figure 3) showed that growth mainly spread from the 'cores', which are the economic engines of agglomeration development, to surrounding areas southward (BTHUA and YRDUA), or eastward (PRDUA). As the capital city, Beijing promoted industrialization and urbanization for the rest of BTHUA without producing the largest NF. The nearby municipality of Tianjin and the adjacent city Tangshan, where most industries were concentrated, played the key roles in regional NF growth (>200 Gg N each), with the former's annual NF exceeding Beijing's since 2015.

Similarly, the municipality of Shanghai and the adjacent city Suzhou had the higher GDP per capita and contributed most to the regional NF growth (>300 Gg N each) in YRDUA. Except for Huzhou in Zhejiang province, the other cities in this province all presented significant NF growths (>100 Gg N each). In contrast, the majority of cities in Anhui province located in the center part of YRDUA had lower NF growths (<50 Gg N each), because of their lower levels of energy consumption compared with the other cities.

Meanwhile, the twin drivers of Guangzhou and Shenzhen promoting NF growths (>300 Gg N each) were observed in PRDUA. Guangzhou, Shenzhen, Dongguan and Foshan are the most economically developed cities in PRDUA, where manufacturing industries are concentrated. These cities attract an enormous number of migrants from the rest of Guangdong and other provinces, resulting in greater food and energy consumption, due to the demands of their rising populations. Therefore, these cities undoubtedly turned out to be the main areas for NF growth, and the highest aggregate risks for N pollution were found in Shenzhen (Dong and Xu 2019).

Notably, the NF growth hotpots in all three urban agglomerations are coastal, indicating that more aquatic Nr (accounting 49%–57% of total NFs in relevant cities) most likely enters the ocean (Xian et al 2019). Nr, as a source of marine pollution, obstructs water quality improvements for the sustainable development of coastal cities, and thus should be a priority of the national strategy for ‘Coordinated Land and Maritime Development’ (MEE 2018).

3.2. Patterns of urban agglomeration NFs

Considering the regional characteristics in the FNF of the three urban agglomerations during 2000–2019 (figure 4), the average proportions of FNF in BTHUA, YRDUA and PRDUA were 57.64%, 68.64% and 66.79%, respectively, which were similar to the national level (68.44%) (Gu et al 2013), except for BTHUA. The decreasing FNF percentages of the three urban agglomeration indicated that the proportions taken up by the ENF rose. In BTHUA, the ENF percentages for Cangzhou, Tangshan and Langfang were 50%, 60% and 62%, respectively. The higher percentages of ENFs were also found in Shaoxing (55%) and Suzhou (52%) in YRDUA. Previous research on national NF accounting found that the ENF increased faster than the FNF, but that the latter still dominated national NF as much as 82% in 2009 (Cui et al 2016). However, our study found that the proportions of FNFs in 81% cities ranged from 51% to 86% in 2010, indicating the fact that the FNFs were not occupying such large percentages, as high as the national level in urban agglomerations. FNFs had significantly high percentages across the cities in 2000 (figure 4), but with the exception of Beijing, began to be in widespread decline, which indicated a rising trend of ENF proportions over the past two decades,
addressing the urgent needs to reduce the ENF of urban agglomerations.

To compare with the NFs of other regions, it may helpful to consider the N management strategies of other regions. The proportions of FN in the studied urban agglomerations were lower than in Japan (91%) (Shibata et al. 2014), the Netherlands (90%) (Leach et al. 2012), Tanzania (87%) (Hutton et al. 2017), Austria (86%) (Pierer et al. 2014), the United Kingdom (84%) (Stevens et al. 2014), Germany (83%) (Stevens et al. 2014) and the United States of America (71%) (Leach et al. 2012), but were close to the level of Australia (69%) (Liang et al. 2016). In other words, the ENF played a more important role in major Chinese urban agglomerations, compared to other developed and developing countries. In general, the per-capita energy consumption in China was lower than in most of the developed countries mentioned above. However, from the perspective of regional NF production, urban agglomeration tended to produce high-proportioned ENF due to the limited control measures to reduce NOx emissions from fossil fuel combustion that mainly occurred in cities (Shibata et al. 2017). In Australia, beef consumption and coal combustion for electricity are key drivers of higher national NF (Liang et al. 2016). Unlike Australia, pork is the main component of meat intake for daily diets in China, and beef is more readily consumed in the regions of Northwest China that have lower URs (Xian et al. 2021).

3.3. Drivers of NFs in China’s major urban agglomerations

Based on the results of the correlation analysis, the NFs of urban agglomerations were not only influenced by UR and GDP per capita, but also correlated with the percentages of GDP occupied by primary, secondary and tertiary industries (table 1). The factors related to economic urbanization had stronger impacts on the NFs of urban agglomerations than population urbanization.

Further analysis reveals the main factors driving the regional NFs. The relevant factors (variance inflation factor values >5) were excluded from the multiple linear regression, and then the standardized coefficient was calculated to determine which socio-economic factor explained most of the variations in the NF of targeted urban agglomeration (table 2). The results showed that the GDP per capita and the percentage GDP of primary industry were the main factors influencing the NF of BTHUA, while the rising UR had accelerated the NF growth of YRDUA. Meanwhile, rising GDP per capita, due to urbanization, contributed to the NF growths of BTHUA and PRDUA, which is consistent with a previous national analysis study (Xian et al. 2019) (see supplementary information text S3 for more detail).

3.4. Projections and reduction strategies for the NFs of major urban agglomerations

If no mitigative actions are taken in BTHUA, YRDUA and PRDUA, regional NFs for these urban agglomerations will increase by 0.6%, 0.1% and 1.3%, respectively, compared with their baseline NFs in 2019, given exiting trends (table 3). Of all the NF mitigation scenarios considered, implementing NF
Figure 4. A chromaticity diagram showing the food NF percentages of cities and urban agglomerations in 2000, 2005, 2010, 2015 and 2019.

Table 1. Coefficients of determination for correlations between NF and socioeconomic factors in major urban agglomerations from 2000 to 2019.

| R-square for correlations | BTHUA NF | YRDUA NF | PRDUA NF |
|---------------------------|----------|----------|----------|
| UR                        | 0.57**   | 0.44***  | 0.28***  |
| PP                        | 0.01     | 0.51**   | 0.04     |
| PS                        | 0.15     | 0.02     | 0.04     |
| PT                        | 0.15     | 0.01     | 0.10**   |
| GDP per capita             | 0.60***  | 0.27***  | 0.46***  |
| PGDP                      | 0.68***  | 0.22**   | 0.20**   |
| SGDP                      | 0.56*    | 0.08*    | 0.16*    |
| TGDP                      | 0.29***  | 0.39***  | 0.56***  |

Notes: *, **, *** represent that the statistics are essential at the 10%, 5%, and 1% levels of significance.

reduction strategies for healthy diet promotion produces the greatest overall reductions of 9.3% and 15.9% in YRDUA and PRDUA, respectively, while the energy friendly scenarios significantly contribute to reductions of 9.7% and 9.0% in BTHUA and YRDUA, respectively. Meanwhile, the rural treatment scenarios have positive impacts on all urban agglomerations with NF reductions from 1% to 2%. Given the aforementioned scenarios considered, the largest total NF reductions in the urban agglomerations can
be achieved by the substitution of 25% of fossil fuel use with non-fossil fuel use. The energy friendly strategies that consider substitutes for fossil fuels also can lead to large carbon footprint reductions (Liang et al. 2018). As expected, the NFs of urban agglomerations will increase as the UR reaches 75% by 2030. In this context, the implementation of multiple measures can lead to greater reductions of NFs; 18.0%, 22.7% and 29.2%, for BTHUA, YRDUA, and PRDUA, respectively. Notably, the positive impacts of improvements in rural wastewater treatment on the NF reduction of PRDUA will be a twofold enhancement, from 1.0% to 2.3%, compared to its actual level in 2019.

In the future, the Healthy Diet scenario, Rural Treatment scenario and Energy Friendly scenarios will require mitigative actions at the national, regional and even personal level. As stated by the leadership at the Climate Ambition Summit in December 2020, China’s commitment to increase non-fossil fuel sources to 25% of the national energy mix has accelerated action in developing strategies to achieve a carbon emissions peak by 2030 and promoting clean energy installation. Therefore, more measures related to further energy reduction have been gradually carried out, including improvements in energy efficiency, the promotion of electric vehicles and the establishment of a carbon emissions trading scheme, indicating the plausibility of an Energy Friendly scenario in the future. In contrast, implementing policy to achieve the Healthy Diet scenario may be challenging. There are significant dietary variations between urban and rural residents; urban residents, typically with higher incomes, consume meat-rich, and subsequently N intense diets, whereas rural residents may consume less meat owing to lower-income levels (Xian et al. 2019, 2021). These dietary variations would require nuanced policy approaches that may not be possible or successful. Therefore, NF reductions associated with dietary changes, compared to NF reductions associated with greater renewable energy use, may receive less political attention or support. However, reducing FNFs are important. Extra FNF reductions (through cutting VNF for crop production) can be achieved in the Jiangsu, Anhui and Hebei provinces that occupy most areas in BTHUA and YRDUA, by optimizing synthetic N fertilization.

It is observed that these provinces have a larger potential for soil nitrous oxide emissions reductions should synthetic fertilizers be applied (Zhang et al. 2019). Therefore, the improvement in N fertilization efficiency, as well as a dietary adjustment with less red meat, should be more widely promoted, which in addition to improving public health will also lessen N effluence and pollution from the perspectives of food production and consumption. The Rural Treatment scenario, specifically implementing wastewater treatment plants in rural areas, could be more readily achieved by local governments if greater financial support were to be available. The potential for NF reduction via the Rural Treatment scenario in China is significant. For example, many developed countries have over 70% of their sewage treated by improved denitrification technologies that are rarely available in many rural areas in China (Shibata et al. 2017). Therefore, making denitrification technologies available in rural areas represents a vital opportunity to further reduce China’s overall NF. The implementation of these N-related management approaches would be priorities in PRDUA driven by the ‘Implementation Plan for the Guangdong Action Plan for Water Pollution and Control’, the major gaseous and aquatic pollutants of which are nitric oxide and ammonium nitrate in recent years (Dong and Xu 2019, Xian et al. 2022).

3.5. Advantages and limitations of applying NFs in the context of urban agglomerations

Regional N management, which involves mutual feedback relationships between human and natural

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Table 2. Summary for multiple linear regression.

| Scenario       | Unstandardized coefficients | Standardized coefficients | Collinearity statistics |
|----------------|-----------------------------|---------------------------|------------------------|
|                | B      | Std. error | Beta       | T       | Sig. (P) | Tolerance | VIF      |
| BTHUA NF       |        |            |            |        |          |           |          |
| Constant       | 445.398 | 59.350 | —          | 7.505 | 0.000    | —         | —        |
| GDP per capita | 0.002  | 0.000 | 0.564 | 4.721 | 0.000 | 0.390 | 2.566 |
| PGDP           | −15.068 | 2.239 | −0.695 | −6.728 | 0.000 | 0.352 | 2.840 |
| TGDP           | −2.853 | 0.920 | −0.298 | −3.102 | 0.003 | 0.407 | 2.457 |
| YRDUA NF       |        |            |            |        |          |           |          |
| Constant       | −84.882 | 64.374 | —          | −1.319 | 0.098 | —     | —        |
| UR             | 5.651  | 0.524 | 0.666 | 10.784 | 0.000 | 0.963 | 1.038 |
| PD             | 8.440  | 2.036 | 0.257 | 4.145 | 0.000 | 0.955 | 1.047 |
| SGDQ           | −2.079 | 1.010 | −0.129 | −2.059 | 0.042 | 0.939 | 1.065 |
| PRDUA NF       |        |            |            |        |          |           |          |
| Constant       | −172.564 | 60.776 | —          | −2.839 | 0.007 | —     | —        |
| GDP per capita | 0.001  | 0.000 | 0.619 | 2.436 | 0.020 | 0.542 | 1.846 |
| TGDP           | 6.527  | 1.609 | 0.530 | 4.055 | 0.000 | 0.542 | 1.846 |
Table 3. NFs and their proportional changes (shown in brackets) for the major urban agglomerations in 2030 with the reductions by specific scenarios.

| Scenarios            | Projected NF changes compared to 2019 baseline (Gg N) | NF reduction relative to the ‘business as usual’ scenario in 2030 (Gg N) |
|----------------------|-------------------------------------------------------|------------------------------------------------------------------------|
|                      | BTHUA                          | YRDUA                             | PRDUA                             | BTHUA                          | YRDUA                             | PRDUA                             |
| Business as Usual    | +21.28 (0.6%)                  | +6.46 (0.1%)                      | +28.30 (1.3%)                     | —                               | —                                 | —                                 |
| Healthy Diet         | −109.40 (3.3%)                 | −457.41 (9.3%)                    | −350.29 (15.9%)                   | −130.68 (3.9%)                  | −463.86 (9.4%)                    | −378.60 (17.0%)                    |
| Rural Treatment      | −67.65 (2.0%)                  | −96.15 (2.0%)                     | −22.85 (1.0%)                     | −88.93 (2.7%)                   | −102.61 (2.1%)                    | −51.15 (2.3%)                      |
| Energy Friendly      | −320.39 (9.7%)                 | −444.59 (9.0%)                    | −185.24 (8.4%)                    | −341.66 (10.2%)                 | −451.05 (9.1%)                    | −213.54 (9.6%)                     |
| Multiple Measures    | −579.48 (17.5%)                | −1111.34 (22.6%)                  | −621.83 (28.3%)                   | −600.75 (18.0%)                 | −1117.79 (22.7%)                  | −650.13 (29.2%)                    |
activities, is a challenging issue to governance, but an essential for sustainable development (Gu et al 2019, Morseletto 2019). Challenged by China’s current policy to promote economic growth through urbanization (Bai et al 2014), China will meet the dilemma that reducing N utilization for food production will not satisfy the needs of such rapid growth in urban population. Therefore, N utilization will accelerate while mitigating Nr loss to the environment. Given there is no single treaty at the level of United Nations for handling all the threats to sustainable development posed by Nr (Morseletto 2019), the NF indicator can serve as an efficient approach to track progress and evaluate the effects of different N management actions for achieving N-related SDGs, in the different urbanized regions of a country as large and rapidly developing as China (Gu et al 2019).

In performing the NF analysis and making projections in the context of urban agglomerations, we can: (a) calculate the regional NFs by adding up their constituent cities’ NFs, in the process of revealing the spatio-temporal characteristics for comparative purposes; (b) reveal rapidly urbanizing regions’ overall contribution to Nr loss and identify which cities have the greatest influence on regional N pollution; (c) make projections and representative scenarios to identify efficient pathways for NF reduction towards sustainable development at the urban and regional scales, based on current policy planning; and (d) address challenges that prevent effective regional NF reduction, by showing the relevant interactions among cities, consequently raising awareness about Nr pollution and the necessity for mitigation based on these interactions, as well as urban-rural connections.

This study nonetheless faced several limitations, and uncertainties inevitably arose due to certain data limitations. The ENF calculation relies on the inventory data for detailed energy use and relevant emission factors in each city, but long-term statistics for such information were lacking, and therefore relevant data were retrieved from provincial averages. In terms of FNF calculation, the regional VNF values were not available, and the statistics for various food consumption per capita were assumed to be similar in the same province. This may affect the accuracy of NF calculation, but it does not affect the analysis of overall trends in NF dynamics and their driving factors, because of the uniform parameters used throughout the assessment. Further research is warranted, focusing on improving the accuracy of NF calculation of urban agglomerations combined with the forecasting of N fertilization efficiency, and the use of best-available data and methods.

4. Conclusions

In this study, we present the first attempt to adapt NF methods to explore the spatial-temporal characteristics of three major urban agglomerations’ NFs and their driving forces in China, aiming at finding general trends and principles for N management, to advance sustainable development in Chinese urban agglomerations. Our results also echo the findings of other studies, in terms of the challenges to NF reductions brought by urbanization, and address that the ENF gradually played a more important role in Chinese urban agglomerations compared to other countries. In the context of current policy trends, the scenario of fossil fuel energy reduction is likely to be the most efficient and plausible for NF reductions of urban agglomerations by 2030—even amid further urbanization. The largest potential NF reductions, contributed by healthy diet, cleaner energy and waste treatment, are predicted for PRDUA (29% reduction), followed by YRDUA (23% reduction) and BTHUA (18% reduction). This study gives us a better understanding of the challenges surrounding the socioeconomic attribution of urbanization to China’s NF. It demonstrates the potential of NF as a tool for assessing the sustainable development of urban agglomerations, highlighting the potential for further reductions of Nr, a key pollution source and threat to environmental health during regional urbanization.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors declare no conflicts of interest.

References

Bai X, Shi P and Liu Y 2014 Realizing China’s urban dream Nature 509 158–60
CNS (Chinese Nutrition Society) 2021 Dietary Guidelines for Chinese Residents (available at: http://dg.cnssoc.org/) (Accessed 10 November 2021)
Cui S, Shi Y, Groffman P M, Schlesinger W H and Zhu Y G 2013 Centennial-scale analysis of the creation and fate of reactive nitrogen in China (1910–2010) Proc. Natl Acad. Sci. 110 2052–7
Cui S, Shi Y, Malik A, Lenzen M, Gao B and Huang W 2016 A hybrid method for quantifying China’s nitrogen footprint during urbanization from 1990 to 2009 Environ. Int. 97 137–45
Dhar A R, Oita A and Matsubak K 2021 The effect of religious dietary cultures on food nitrogen and phosphorus footprints: a case study of India *Nutrients* 13 1926

Dong Y and Xu L 2019 Aggregate risk of reactive nitrogen under anthropogenic disturbance in the Pearl River Delta urban agglomeration *J. Clean. Prod.* 211 490–502

Elrys A S, Raza S, Abdo A I, Liu Z, Chen Z and Zhou J 2019 Budgeting nitrogen flows and the food nitrogen footprint of Egypt during the past half century: challenges and opportunities *Environ. Int.* 130 104895

Erisman J W 2004 The Nanjing declaration on management of reactive nitrogen *Biogeochemistry* 54 286–7

Fang C, Cui X, Li G, Bao C, Wang Z, Ma H, Sun S, Liu S, Liu K and Ren Y 2019 Model building scenarios using the urbanization and eco-environmental coupler: case study of Beijing-Tianjin-Hebei urban agglomeration, China Sci. *Total Environ.* 689 820–30

Fang C and Du D 2017 Urban agglomeration: an evolving concept of an emerging phenomenon *Landscape Urban Plan.* 162 126–36

Galloway J N, Aber J D, Erisman J W, Seitzinger S P, Howarth R W, Cowling E B and Cosby B J 2003 The nitrogen cascade *Biogeochemistry* 53 341–36

Gao J, Shao C, Chen S and Zhang X 2021 Spatiotemporal evolution of sustainable development of China's provinces: a modelling approach *Ecosyst. Health Sust.* 7 737–50

Gu B et al 2019 Toward a generic analytical framework for sustainable nitrogen management: application for China *Environ. Sci. Technol.* 53 1109–18

Gu B, Leach A M, Ma L, Galloway J N, Chang S X, Ge Y and Chang J 2013 Nitrogen footprint in China: food, energy, and nonfood goods *Environ. Sci. Technol.* 47 9217–24

Guo M, Chen X, Bai Z, Jiang R, Galloway J N, Leach A M, Cattaneo L R, Onemba O, Ma L and Zhang F 2017 How China's nitrogen footprint of food has changed from 1961 to 2010 *Environ. Res. Lett.* 12 104006

Hutton M O, Leach A M, Leip A, Galloway J N, Bekunda M, Sullivan C and Lesschen J P 2017 Toward a nitrogen footprint calculator for Tanzania *Environ. Res. Lett.* 12 034016

Leach A M, Galloway J N, Bleeker A, Erisman J M, Kohn R and Kitas J 2012 A nitrogen footprint model to help consumers understand their role in nitrogen losses to the environment *Environ. Dev.* 1 40–66

Liang X, Leach A M, Galloway J N, Gu B, Lam S K and Chen D 2016 Beef and coal are key drivers of Australia’s high nitrogen footprint *Sci. Rep.* 6 39644

Liang X, Ng E L, Lam S K, Castrén E A, Leach A M, Gu B, Healey G, Galloway J N and Chen D 2018 The nitrogen footprint of an Australian university: institutional change for corporate sustainability *J. Clean. Prod.* 197 534–41

McCourt S and MacDonald G K 2021 Provincial nitrogen footprints highlight variability in drivers of reactive nitrogen emissions in Canada *Environ. Res. Lett.* 16 095007

MEE (Ministry of Ecology and Environment of China) 2018 Strength marine environmental protection under the principle of coordinating land and sea development (available at: www.mnr.gov.cn/dt/hy/201812/t20181212_4379047.html) (Accessed 10 November 2021)

Morseretto P 2019 Confronting the nitrogen challenge: options for governance and target setting * Glob. Environ. Change 54 40–49

Pierer M, Winiwarter W, Leach A M and Galloway J N 2014 The nitrogen footprint of food products and general consumption patterns in Austria *Food Policy* 49 126–36

SCC (State Council of China) 2020a National Population Development Program (2016–2030) (available at: www.gov.cn/zhengce/content/2017-01/25/content_5163309.htm) (Accessed 10 November 2021)

Shi Y, Cui S, Ju X, Cai Z and Zhu Y 2015 Impacts of reactive nitrogen on climate change in China *Sci. Rep.* 5 8118

Shibata H et al 2017 Nitrogen footprints: regional realities and options to reduce nitrogen loss to the environment *Ambio* 46 120–42

Shibata H, Cattaneo L R, Leach A M and Galloway J N 2014 First approach to the Japanese nitrogen footprint model to predict the loss of nitrogen to the environment *Environ. Res. Lett.* 9 115013

Steffen W et al 2015 Planetary boundaries: guiding human development on a changing planet *Science* 347 1259855

Stevens C J, Leach A M, Dale S and Galloway J N 2014 Personal nitrogen footprint tool for the United Kingdom *Environ. Sci.-Proc. Imp.* 16 1563–9

Sutton M A, Howard C M, Erisman J W, Billen G, Bleeker A, Grennfelt P, van Grinsven H and Grizzetti B 2011 *The European Nitrogen Assessment: Sources, Effects and Policy Perspectives* (Cambridge: Cambridge University Press)

Vitousek P M, Aber J D, Howarth R W, Likens G E, Matson P A, Schindler D W, Schlesinger W H and Tilman D 1997 Human alteration of the global nitrogen cycle: sources and consequences *Ecol. App.* 7 737–50

Wei D, Liu Y and Zhang N 2019 Does industry upgrade transfer pollution: evidence from a natural experiment of Guangdong province in China *J. Clean. Prod.* 229 902–10

Wiedmann T and Lenzen M 2018 Environmental and social footprints of international trade *Nat. Geosci.* 11 314–21

Xia Y, Liao C, Wu D and Liu Y 2020 Dynamic analysis and prediction of food nitrogen footprint of urban and rural residents in Shanghai *Int. J. Environ. Res. Public Health* 17 17509

Xian C, Fan Y, Zhang J and Zhang L 2022 Assessing sustainable water utilization from a holistic view: a case study of Guangdong, China *Sustain. Cities Soc.* 76 103428

Xian C, Gong C, Lu F, Zhang L and Ouyang Z 2021 Linking dietary patterns to environmental degradation: the spatiotemporal analysis of rural food nitrogen footprints in China *Front. Nutr.* 8 717640

Xian C and Ouyang Z 2016 Calculation and dynamic analysis of the food nitrogen footprints of urban and rural residents in Beijing *Acta Ecol. Sin.* 36 2413–21 in Chinese with English abstract

Xian C, Ouyang Z, Lu F, Xiao Y and Li Y 2016 Quantitative evaluation of reactive nitrogen emissions with urbanization: a case study in Beijing megacity, China *China Environ. Sci. Technol.* 46 1290–280

Xian C, Zhang X, Zhang J, Fan Y, Zheng H, Salzman J and Ouyang Z 2019 Recent patterns of anthropogenic reactive nitrogen emissions with urbanization in China: dynamics, major problems, and potential solutions *Sci. Total Environ.* 656 1071–81

Yu X, Wu Z, Zheng H, Li M and Tan T 2020 How urban agglomeration improve the emission efficiency? A spatial econometric analysis of the Yangtze River Delta urban agglomeration in China *J. Environ. Manage.* 260 110061

Zeng Y, Xu C, Wang Q, Li Y and Hou S 2019 Basin-scale estimation of nitrogen footprint and corresponding dynamic change characteristics: a case study *Environ. Res. Lett.* 29 81–93

Zhang G, Sun B, Zhao H, Wang X, Zheng C, Xiong K, Ouyang Z, Lu F and Yuan Y 2019 Estimation of greenhouse gas mitigation potential through optimized application of synthetic N, P and K fertilizer to major cereal crops: a case study from China *J. Clean. Prod.* 237 117650

Zhou W, Yu W, Qian Y, Han L, Pickett S T, Wang L, Li W and Ouyang Z 2021 Beyond city expansion: multi-scale environmental impacts of urban megaregion formation in China *Nat. Sci. Rev.* 9 mwa107