ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

The nitrogen footprint of Ukraine: why personal consumption matters

To cite this article: Sergiy Medinets *et al* 2024 *Environ. Res. Lett.* **19** 024023

ENVIRONMENTAL RESEARCH
LETTERS

LETTER

OPEN ACCESS

RECEIVED
10 September 2023

REVISED
20 December 2023

ACCEPTED FOR PUBLICATION
15 January 2024

PUBLISHED
25 January 2024

The nitrogen footprint of Ukraine: why personal consumption matters

Sergiy Medinets[1,2,3,*], Allison M Leach[4], Tetiana Pavlik[2], Volodymyr Medinets[2] and James N Galloway[5]

1 Atmospheric Chemistry and Effects, UK Centre for Ecology & Hydrology, Edinburgh, EH26 0QB, United Kingdom
2 Regional Centre for Integrated Environmental Monitoring, Odesa National I. I. Mechnikov University, 65082 Odesa, Ukraine
3 Department of Agroecology, Aarhus University, 8830 Tjele, Denmark
4 The Sustainability Institute, University of New Hampshire, Durham, NH 03824, United States of America
5 Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22904-4123, United States of America
* Author to whom any correspondence should be addressed.

E-mail: s.medinets@gmail.com

Keywords: nitrogen footprint, N loss, N waste, diet, food protein supply

Supplementary material for this article is available online

Abstract

Unintended reactive nitrogen (N) losses from agriculture, energy and transportation pose significant environmental hazards, including eutrophication, acidification, water and air pollution, biodiversity loss, human health risks and climate change. The concept of a nitrogen footprint (NF) emerges as a pivotal metric, reflecting potential N losses in the entire production-consumption chain of goods and services used by an individual within a defined timeframe.

In a pioneering assessment of per capita NF in Ukraine, key factors, such as the food production chain, consumption patterns, connection to wastewater treatment (WWT) system and the efficacy of WWT facilities, were identified as critical components. Addressing specific challenges, such as data availability, soil N depletion and manure waste, was found to be particularly complex. The apparent high nitrogen use efficiency in Ukrainian cropping systems was highlighted to be actually reflected in the elevated N mineralization rate in Ukrainian soils characterized by high organic matter content. The individual Ukraine NF (22.1 kg N cap^{-1} yr^{-1} as of 2017) was found to be much lower than that of the US and Australia being comparable to Western European countries. Even so, significant opportunities for reduction remain through a wide range of options towards healthier and more sustainable dietary choices. Potential reductions, ranging from 22% to 69%, were shown for omnivore, reduced red meat, no red meat, half meat products, vegetarian and vegan diets. In the absence of proper manure management in Ukraine, even greater reductions of an 'actual' NF can be achieved if wasted N manure is considered.

The war's impact is assumed to result in a slight increase or no changes in individual food consumption NFs and an increase in food production NFs for local products, while reductions in individual transport and energy NFs were likely across Ukraine. Nonetheless, refugees massively displaced to less affected regions overload a largely outdated civilian infrastructure, leading to higher N losses.

Looking ahead, sustained support, capital investments, legislative enhancements and regulatory frameworks, especially upon post-war renovation of Ukraine, are imperative for reducing the individual NF. This involves enhancing nitrogen use efficiency in agriculture, establishing efficient manure management, upgrading WWT facilities, promoting renewable energy adoption, bolstering requisite infrastructure and raising public awareness on environmental sustainability.

1. Introduction

Nitrogen (N) in a form of reactive N (N_r; i.e. N in any form except N_2) is a vital nutrient for all living organism. Ensuring an adequate N input is crucial to sustain crop productivity for food and feed production (Galloway and Cowling 2021). However, N surplus, resulting from increased N input and/ or improper management (including failure to follow 4 R nutrient stewardship: right fertilizer type, right amount, right placement, and right time), leads to unintended N loss from agricultural systems (Sutton *et al* 2022). This loss causes numerous environmental threats, such as eutrophication, acidification, drinking water pollution, air pollution, biodiversity loss, human health risks, greenhouse gas emissions (Sutton *et al* 2011, 2022, Galloway *et al* 2021). For example, in Ukraine synthetic N fertilizer use increased in 1.7-fold over 2010–2017, while application of manure had remained dramatically low (∼10%) marking animal farming as a big N pollution source (Medinets *et al* 2024a).

According to global security projections systematized by Van Dijk *et al* (2021), global food consumption is expected to increase by 30%–62% between 2010 and 2050, due to both a growing global population (predicted to reach 10 billion) and increased per capita food consumption. They estimated that per capita food consumption may increase by 0%–20%.

Another significant source of nitrogen pollution is energy use, or more specifically, fossil fuel combustion. End-use power consumption in the residential sector for heating/cooling households, appliances, personal equipment and transportation (both personal and public) will increase globally due to population growth and improved living standards in developing countries. Global electricity use is forecasted to increase by about 50% by 2050 (IEO 2021). As of 2021, ∼62% and ∼38% of global energy was generated from fossil fuels (incl. 36.5% from coal) and clean sources (incl. 10.3% from wind and solar) respectively (Ember 2022); the share of renewables will increase, while the use of coal depends on countries' practical implementation of their net zero ambitions to limit global warming to 1.5 °C by 2050 (GECO 2022). In Ukraine, we anticipate a significant transition to clean and renewable energy sources as the country energy sector is reconstructed in the post-war period. However, we expect an enormously high energy demand during the recovery of infrastructure and the industrial sector.

The N footprint (NF) concept has been proposed to evaluate and highlight the extent of human contribution to nitrogen pollution, specifically through personal consumption patterns involving food, energy, goods and services. This evaluation can be done at various scales, ranging from individual to country levels, considering the subsequent effects on the environment and human health (Leach *et al* 2012, Einarsson and Cederberg 2019). The NF serves as an indicator of potential N losses/wastes throughout the entire production–consumption chain of all products and services consumed or used by an individual over a certain period (Leach *et al* 2012, Shibata *et al* 2017). Although an individual may change what they consume or use, there are also aspects of the infrastructure and supply chain that are beyond the individual's control. For example, these user-independent parts are related to the technological level of certain food production and processing, energy generation sources, waste recycling facilities provided by government (e.g. wastewater treatment (WWT) quality, solid waste collection and processing), and, of course, any national regulatory standards in place. Therefore, a country's average personal NF not only reflects the preferences and consumption behavior of the population at a national level but also highlights the sustainability of that country's agriculture, energy, transport, and waste management sectors.

The variation in per capita NF among regions is widely recognized, but most N losses to the environment occur in the food production–consumption chain (Galloway *et al* 2014, McCourt and MacDonald 2021). In developed countries where households are mostly connected to WWT facilities or have advanced WWT systems, the excretion of N by humans is not considered a significant source of N loss to the environment if most of it recycled or denitrified (Leach *et al* 2012, Pierer *et al* 2014, Stevens *et al* 2014). However, this is not the case in countries and regions with inadequate sanitation facilities as well as those with a low percentage of households connected to WWT systems. According to the World Health Organization (WHO 2019), approximately 70% of the global population had access to basic sanitation, while only 45% used a safely managed sanitation service, which involves containment, safe collection and conveyance, treatment, and appropriate end-use or disposal. The absence or poor quality of waste treatment facilities pose risks to human health and raise several environmental concerns. That said, upgrading WWT facilities (including plants and wastewater collection) to meet EU standards and maintaining them comes with significant costs, which poses a major challenge for many Eastern European countries, regardless of their EU status (Rozenberg and Fay 2019).

This study aimed to assess for the first time the per capita Ukraine NF, which provides an estimate of the potential contribution of an average Ukrainian's consumption pattern, categorized by main components, to N pollution. Additionally, it provided an insight of the current state of wastewater management in Ukraine, estimated the potential release of physiological N from a healthy human, discussed the impact of dietary changes on N pollution and human health, and proposed recommendations for reducing personal NFs.

2. Methods

2.1. Study area and boundaries

This study considered domestic consumption by the population in Ukraine, including both the production of food and energy associated with it. Ukraine is one of the biggest European countries with area of 603 628 km^2, located within the Black Sea basin. For this study the year 2017 was selected as a recent and representative year with the availability of necessary data sets from the Food and Agriculture Organization (FAO 2023) and the State Statistics Service of Ukraine (SSSU 2018) at the time when this research launched in 2020. The population in 2017 was 42.4 million people, excluding the population living in temporary occupied territories, such as Crimea and the parts of Luhansk and Donetsk regions, as those data were not kept by SSSU. Around 69% of population (29.4 million) lived in urban areas in 2017, but this varied substantially by region: The administrative regions in Eastern Ukraine were urban-dominated, whereas, on average, in the Western region, the population was nearly equally distributed between urban and rural areas (figure S1 and table S1). On average a Ukrainian household consisted of 2.58 person units (SSSU 2018).

The agricultural sector in Ukraine mainly focuses on crop production. Cereals were the predominant crops, most of which were produced for export (corn—82%, wheat—65%, barley—50% for 2017), followed by sunflowers (87% and 75% of produced sunflower oil and meal exported respectively) (SSSU 2018). Around 1700 Gg N was harvested from agricultural land as crop yield in 2017. Ukrainian croplands generally received insufficient-to-moderate amount of N (mainly synthetic) and characterized with modest fertilizer-induced emission factors (EFs) for N_2O and NO (Medinets *et al* 2016, 2021). Poultry (both meat and eggs production) and dairy were the main contributors in the livestock sector (SSSU 2018). In 2017, totally 126 Gg N was produced with animal products in Ukraine.

2.2. Data for N footprint calculation

The NF is composed of the N loss from food, housing, transportation, goods and services. The methodology used in this study was based on the N-Calculator model developed by Leach *et al* (2012) and used elsewhere since then (e.g. Shibata *et al* 2014, Stevens *et al* 2014, Liang *et al* 2016). In this study, it was assumed that all consumed products and resources consumed were produced within Ukraine. As a result, losses and wastes of Nr originating from the production chains of imported products and resources were not separately accounted for due to a lack of data.

2.2.1. Food component

There are two sub-components of food NF: food consumption (from retail via the consumer table) and food production (from a field via a full production chain to a retail store) of what is consumed. To quantify food N consumption, we use food protein supply data for different types of products per capita for Ukraine derived from FAO (2023). Then, the protein mass was converted to N mass (on average protein consists of 16% N). The food N wastes upon distribution and consumption were calculated using FAO reports (Gustavsson *et al* 2011, Themen 2013). Then those N wastes were subtracted from N supply to quantify an actual N consumed. We assume that the majority of N from consumed proteins by an average adult, unless they are athletes aiming to gain muscle mass, are excreted (Smil 2002a, Maughan *et al* 2013, Di Girolamo *et al* 2017). In addition, to quantify mean weighted food N consumption losses we calculated how much N was removed upon secondary WWT, using the percentage of population connected to this WWT system, and mean N removal efficacy of operated WWTP (see section 2.2). We assume that removed N_r was likely partially denitrified (converted to N_2), immobilized, re-used or recycled, however it is not often a case for Ukraine (country wide data unavailable).

Losses of N_r related to the food production chain of consumed food were calculated through virtual N factors (VNFs) for each basic food category (Galloway *et al* 2007, Leach *et al* 2012). The VNFs account for all losses of N_r inputs in a system, including unused synthetic and organic fertilizers by plants, crop residues that are not used in food production, feed that is not integrated into animal products, and any lost plant or animal products throughout postharvest handling, storage, processing, packaging, and distribution to retailers (see Leach *et al* 2012 for details).

Both statistical data and a farmer questionnaire survey were used for calculation of the VNFs for crop categories according to the approach by Leach *et al* (2012). Through questionnaires, we collected detailed information from farmers on specific crop management practices, fertilizer rates, yields, by-products and crop/ plant residues across the country, and cross-checked these data with information reported in national statistics (SSSU 2018). However, in a half of crop categories (tomato, corn and fruits) the crop N uptake efficiencies, i.e. the ratios of N in the whole plant to N applied, were higher than 1, indicating that more N was removed by the plants than applied with fertilizers and crop residues. This could be due to unaccounted N sources or soil N mining, especially in the Black soils with a high humic substance content (Bilanchyn *et al* 2021). To address this, we alternatively developed 'a budget' approach that considers additional N sources such as atmospheric deposition (Medinets *et al* 2020b, 2024b), free-living biological N fixation, seeds, and irrigated water (Tsurkan *et al* 2021). However, unless we estimate the N-mineralization rate across Ukraine, which is expected to be significant based on scarce field data (2024a), this budget approach is likely incomplete. Therefore, to ensure comparability with other countries and because the VNF is a loss-based metric, we decided to manually correct the crop N uptake efficiencies (where applicable) by setting them equal to 1 (that is 100%), which in reality was significantly less if N-mining rates would be taken into account. This means that it was assumed that 100% of N applied was taken up by the crop. Because the VNFs aim to estimate the total N lost to the environment—regardless of the source—the latter approach was used for the NF calculations.

Owing to lack of required animal data in Ukrainian statistics and unwillingness of livestock enterprises to participate in questionnaire surveys, we used a modified top-down approach suggested by Shindo and Yanagawa (2017). We calculated N conversion efficiency (NCE) according to this approach, which in its turn was based on a modified approach of Smil (2000, 2002b) (see Shindo and Yanagawa 2017 for details); the feed consumption data were derived from Food Balance Sheet of FAOSTAT (FAO 2023), while forage production data were taken from national statistics, because fodder crop and pasture consumption data were not available for Ukraine in the Organization for Economic Cooperation and Development database.

2.2.2. Energy component

Energy consumption data by households were taken from official Ukrainian statistics (SSSU 2018). To estimate N_r losses from energy consumption we used EFs provided by IPCC (2006) for all categories except of electricity, where we utilized the EF for the US from Sieminski (2015) (see table S2).

Transport data were more challenging in terms of private car categories as there was no official freely available data on the number of cars equipped with petrol, diesel, and gas engines. Therefore, we used own estimations that 77% of private cars are petrol, 15% are diesel and 8% are gas, which were based on mass media information, questionnaires and per. comm. with transport departments. Most EFs we used to quantify N_r emission were those reported for Netherlands (see CBS 2018). In addition, EFs for natural gas cars, petrol motorcycles and railway were based on the US Energy Information Administration (Sieminski 2015). All EFs are listed in table S3.

2.2.3. Wastewater management data

Data on the population connected to domestic WWT in 2017 were taken from official national statistics of Ukraine (SSSU 2018) as we found that FAO estimates were systematically higher than those reported by SSSU. Due to the limited information on the share of the population (households) supplied by advanced, secondary, primary WWT and no treatment facilities (out of order, malfunctioned etc) in annual official statistics, we decided to use data from recently published governmental report (Renewal 2022), assuming that WWT facilities have not been updated substantially at a country scale between 2017 and 2021.

Another big challenge was related to the efficacy of WWT plants (WWTP) to remove reactive N from wastewaters. Those data were not publicly available and even could not been shared upon a university request. We found scarce 'gray' literature published in Ukrainian on this topic (e.g. Dolina 2011, Tuchkovenko Yu *et al* 2020) and then used the mass balance approach to roughly quantify the mean N removal efficacy of WWTP operated in Ukraine. The higher nutrient loads resulting *inter alia* from these factors impact the rivers and Black Sea coastal areas, leading to eutrophication events (Kovalova *et al* 2010, Medinets *et al* 2020a, Kovalova *et al* 2021).

2.3. Physiological N excretion

The calculation of physiological N release from humans, which includes excretion, exhaling, and sweating, was conducted based on peer-reviewed studies and medical norms adopted in Ukraine (MHU 2023). The average daily amount of urine, including the concentrations of N-bearing compounds such as urea, ammonium-N, uric acid, and proteins, as well as the average amount of feces with a total N content, excreted by a healthy adult, were estimated following the methodology outlined by Rose *et al* (2015) and the medical norms set by the Ministry of Health of Ukraine (MHU 2023). The average ammonia (NH_3) content in exhaled air and the rate of its excretion through sweating in healthy adults were estimated based on the research of Sutton *et al* (2000). The concentration of nitric oxide (NO) in exhaled air was calculated using the approach described in Medinets *et al* (2015).

2.4. N footprint calculator for Ukraine

To estimate average portion sizes of food consumed by Ukrainians we conducted a survey questionnaire asking about average portion size served (daily/weekly), consumption of main food product/ categories over a week period per household, household structure (amount of persons, gender, age), type of specific diet if any (e.g. vegan, vegetarian, pescetarian, omnivore) through partner institutions and social media. We collected more than 80 responses from households consisting of 2–4 persons.

3. Results

3.1. Wastewater system: household connection and efficacy

Connection of households to WWT system is still a big challenge specifically in rural areas. As of 2017, 64% of the population of Ukraine was officially connected to WWT facilities (SSSU 2018). However, wastewater from 1/3 of this population was left untreated due to malfunctions of the collection and/or treatment facilities at different stages (Renewal 2022). Therefore, according to the latest report (Renewal 2022) domestic wastewater from nearly 43% of the population was supposed to be treated, while only 32% through'a complete biological cycle of wastewater treatment' [a translation from Ukrainian] (figure S2). The latter is likely supposed to be referred to secondary and possibly advanced treatment standards. However, there were no freely available official information regarding the 'complete biological cycle of WWT' procedure for nutrient elimination. It remains unclear whether advanced WWT (including denitrification) was employed and the extent to which it was implemented. Furthermore, there is no indication as to whether WWT by-products underwent recycling or re-use, and if so, then how. Therefore, we decided not to consider the 'complete biological cycle of WWT' facilities in a way to potentially reduce the human NF.

Another issue is existing, mostly outdated, and overexploited, WWTPs. To that, absence of publicly available official inventory on the efficacy and loads of WWTPs made the wastewater sector untransparent. Based on scarce and fragmented data (Dolina 2011, Tuchkovenko Yu *et al* 2020) we roughly estimated using mass balance approach that the N removal rate of a typical WWTP operated in a big town with population over 1 million people ranged between 45%–56% (on average: 51%), but may vary substantially between regions.

3.2. N supply

According to the FAO (2023), an average Ukrainian consumed around 13.7 kg animal proteins per year (or 2.18 kg N cap^{-1} yr^{-1}). Milk products were found to have the largest share (29.4%), followed by poultry meat (20.3%), pig meat (13.2%), eggs (11.3%), fish and seafood (8.4%), beef (7.8%), cheese (5.7%) etc (figure S3(b)). Meanwhile, annually ca. 17.6 kg proteins (or 2.82 kg N cap^{-1} yr^{-1}) were consumed by an adult Ukrainian as plant-based food, where cereals dominated (71.8%) followed by starchy roots (11.9%), vegetables (9.6%) etc (figure S3(a)). Overall, gross protein food consumption of a Ukrainian was 5 kg N yr^{-1} (FAO 2023), while actual (net) consumption was 0.86 kg N yr^{-1} less assigned to customer food N wastes upon a final distribution and consumption.

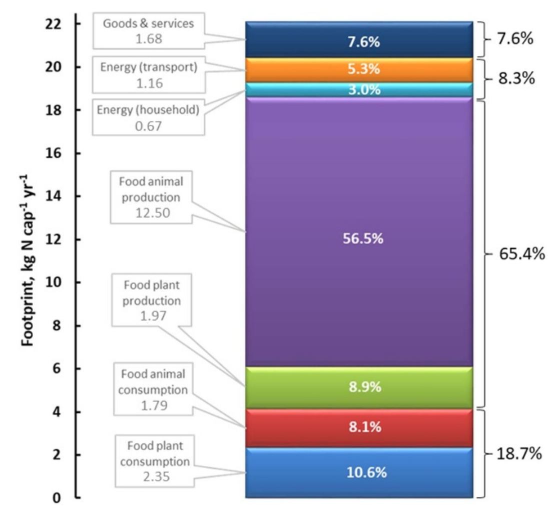

Figure 1. The total annual N footprint of an average Ukrainian for 2017.

3.3. N footprint

The total annual NF of an average Ukrainian was estimated to be 22.1 kg N for 2017 (figure 1).

Food NF consisted of two main components: food consumption wastes (as a matter of a diet, preferences, purchasing power) and food production losses (as a matter of agri-practices, methodologies, and standards typical for Ukraine). Consumption of plant and animal food led on average to 2.35 and 1.79 kg N cap^{-1} yr^{-1} wastes to the environment, respectively (figure 1). Cereals (71.9%), starchy roots (11.5%) and vegetables (9.3%) were the main contributors for plant-based human wastes (figure S4(a)), while milk (29.3%), poultry meat (20.0%), pig meat (13.0%) and eggs (11.8%) formed basic animal-based human wastes (figure S4(a)).

If theoretically 'the complete biological cycle of WWT' in Ukraine included denitrification process (i.e. was equal to advanced WWT), the reduction of the mean food consumption NF (4.14 kg N cap^{-1} yr^{-1}) by 16.3% (or 0.67 kg N cap^{-1} yr^{-1}) would be expected.

Much higher N losses were originated through the animal food production chain (12.5 kg N cap^{-1} yr^{-1}) compared to plant food production (1.97 kg N cap^{-1} yr^{-1}) (figure 1). The largest contributors across the animal production category were pig (27.5%), beef cattle (25.0%), dairy cows (17.6%) followed by poultry (12.5%) farming (figure S5(b)). Wheat (58.3%), starchy root (29.5%) and vegetable (7.5%) production chains generated higher N losses across the plant production category (figure S4(b)). The VNFs we calculated for different categories of animal and crop production chains are presented in table S4.

Overall, the total N food component contributed to 84.1% of the total NF, with 65.4% being lost to the environment during the food production chain and 18.7% being wasted upon food consumption (figure 1).

Energy NF consisted of housing and transportation components and was much lower than the food NF. Around 0.67 and 1.16 kg N were emitted to the environment at energy consumption for household keeping and as a result of transport use by an average Ukrainian over 2017 (figure 1). Higher N losses identified for natural gas consumption (59.6%) mainly in households having individual gas boilers followed by central heating use (17.9%) in households connected to external heating stations (so-called central heating system), electricity utilization (12.8%) and biodiesel use (8.2%); contribution of coal and oil products for personal use to N loss was minor (figure S6(a)). Emission of N due to individual petrol car use dominated (57.8%) across transportation component followed by trains (18.9%), fuel-powered public transport (10.8%), airplanes (5.9%) and individual motorcycles (3.2%). Other categories, including electric public transport contributed insignificantly to total N pollution from transport used by citizens in Ukraine (figure S6(b)).

NF of goods & services use could not be accurately estimated as those data were not kept in Ukrainian statistics. However, we assume based on various fragmented information in mass media, on internet and personal communication that a Ukrainians seemed to be purchased/ renewed (cheaper) goods and use services more frequently than citizens in Western Europe but rarely than those in the US. Therefore, we roughly estimated this category to be 1.68 kg N cap^{-1} yr^{-1} as an average between the UK (having higher magnitude in Europe) and US (Leach *et al* 2012, Leach *et al* , Stevens *et al* 2014; see table S5).

3.4. Physiological N excretion

As a comparison to the food consumption NF, we alternatively quantified the ranges of how much N is expected to be excreted/ released from a healthy adult. It is known that the largest portion of N is excreted from humans via urine and feces, much less via sweating and minor via exhaling. E.g. it was estimated that a healthy adult exhales ca. 3 g N–NH_3 and 0.012 g N–NO annually (Sutton *et al* 2000, Medinets *et al* 2015). Upon sweating over a year period, a healthy human typically releases around 14 g N–NH_3 (Sutton *et al* 2000). According to the medical norms adopted in Ukraine (MHU 2023), we have estimated that daily excretion with urine from healthy adult normally varied in a range of 11.5–16.1, 0.07–0.40 and 0.018–0.024 g N cap^{-1} d^{-1} in a form of urea, uric acid and proteins respectively or in total 4.2–6.0 kg N cap^{-1} yr^{-1}. Whereas with feces a human typically excretes from 0.25 to 2 g N d^{-1} (or 0.1–0.7 kg N cap^{-1} yr^{-1}). In total, we have assessed that one healthy person may physiologically release 4.3–6.8 kg N yr^{-1} (or 11.8–18.8 g N d^{-1}).

4. Discussion

4.1. N Footprint

Mean per capita NF quantified for Ukraine (22.1 kg N cap^{-1} yr^{-1}) was in a range (20.1–23.7 kg N cap^{-1} yr^{-1}) for EU states having country-wide advanced WWT facilities (Austria, Netherlands and Germany), lower than that (27.1–28.7 kg N cap^{-1} yr^{-1}) for European countries with not well-implemented advanced WWT (UK and Portugal) (figure 2 and references there in). Additionally, Ukrainian NF was substantially lower (1.7–2.2 times) than those for the US and Australia (Liang *et al* 2016, Leach *et al*).

4.1.1. Energy and goods components

Average energy use for housing in Ukraine led to a footprint of 0.7 kg N cap^{-1} yr^{-1}, which was in line with Portugal, Netherlands, Austria and Japan, 2.4–3.0-fold lower than in Germany and the UK as well as substantially lesser (3.1–13.1-fold) compared to the US and Australia (figure 2 and references therein). Due to Ukraine's larger territory situated in a continental climate zone, characterized by warm summers and moderately cold winters with occasional short periods of extreme sub-zero temperatures, a significant portion of household energy consumption is dedicated to heating, utilizing natural gas, central heating facilities, and electricity (figure S6). By accelerating the increase in Ukraine's renewable energy share of total energy consumption, which has risen gradually from 6.7% in 2017 to 9.2% in 2020 (SAEE 2021), and implementing energy-efficient technologies for house insulation, both individual housing footprints and operational costs can be significantly reduced.

Ukrainians in their everyday life travel relatively short distances and their average transport footprint (1.2 kg N cap^{-1} yr^{-1}), coming predominantly from individual petrol vehicle use, was like those for Netherlands and the UK but 1.4–1.6 times less than in Germany, Austria and Australia and dramatically lower (4.0 times) than in the US (figure 2 and references therein). To expedite the transition from fossil fuel to electric (and mechanical) vehicles and encourage the shift from individual to public transport use, government incentives such as subsidies and tax exemptions for electric vehicles, along with initiatives like promoting e-charging infrastructure, establishing low emission zones, improving public transportation, and developing bicycle infrastructure, can collectively contribute to reducing individual footprints and creating cleaner cities (Buehler *et al* 2017, Biresselioglu *et al* 2018). Furthermore, utilizing shared car options such as car-sharing services and carpooling is expected to minimize individual environmental impact. E.g. car-sharing in urban areas has the potential to reduce individual mobility emissions by up to 18% annually (Amatuni *et al* 2020).

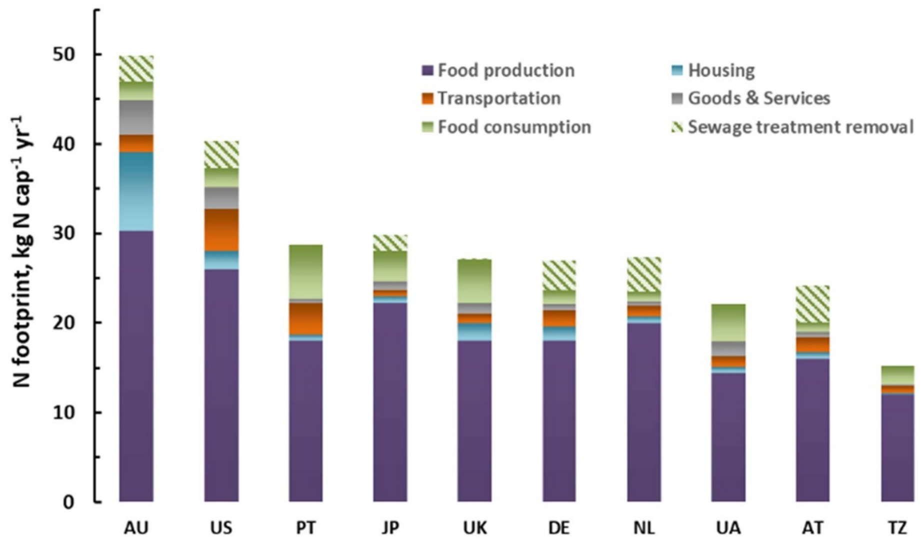

Figure 2. Comparison of country N footprints across the world calculated using N-Calculator approach based on Leach *et al* (2012) [AU: Australia (Liang *et al* 2016); US: United States of America (Leach *et al*); PT: Portugal (Gonçalves 2013); JP: Japan (Shibata *et al* 2014); UK: United Kingdom (Stevens *et al* 2014); DE: Germany (Stevens *et al* 2014); NL: Netherlands (Leach *et al* 2012); UA: Ukraine (this study); AT: Austria (Pierer *et al* 2014); TZ: Tanzania (Hutton *et al* 2017); see also table S5].

The footprint of goods & services use (1.7 kg N cap^{-1} yr^{-1}) was roughly assessed to be larger than in Western Europe but lower than in the US (Leach *et al* 2012). Potential options for N loss and waste reduction in this category lie in a sharing economy concept, including sharing, renting, exchanging, redistributing and donating goods, skills, knowledge via peer-to-peer, neighboring community, social media or commercial platforms (Heinrichs 2013).

4.1.2. Food component

The amount of N consumed with food proteins in Ukraine (5 kg N cap^{-1} yr^{-1}) was in the range of developed countries worldwide (5–6 kg N cap^{-1} yr^{-1}; Leach *et al* 2012, Pierer *et al* 2014, Liang *et al* 2016), but 1.5–1.8 time higher than in Sub-Sahara Africa (2.8–3.3 kg N cap^{-1} yr^{-1}; Abrahams *et al* 2011). Upon the dietary preferences or due to purchasing power limitations, Ukrainians consumed 44% proteins of animal origin. This evidenced on quite a balanced diet and ranged Ukraine, a country with 'transitional economy', in between developed and developing countries consuming much higher (63%–74%) and much lower (17%–30%) animal food proteins, respectively (Obiero *et al* 2019, FAO 2023). By assessing a national Ukrainian food production market capacity vs. citizen consumption needs as of 2017, we revealed that *ca.* 7% of locally produced crop products may completely supply the public needs in plant proteins, whilst to satisfy public demands up to 73% of locally produced animal products are required.

The food sector is the major contributor (69%–92%) to the total NF across all countries (figure 2 and references therein), including Ukraine (84.1%). The largest N losses originated from the food production chain, accounting for 75%–95% of the food NF, and governed mainly by both customer demands (e.g. religious beliefs, dietary preference) and agri-technologies in use (e.g. Dhar *et al* 2021, Einarsson *et al* 2022). Nitrogen use efficacy (NUE) and sustainability of the entire production chain can be assessed and compared through the VNF parameterization, which reflects loss to the environment in kg N upon production per net kg N consumed (Leach *et al* 2012). We found that crop VNFs in Ukraine were below (vegetables, fruits and cereals) or close (legumes) to the lower limit of a range across other countries (table S4 and references therein). The main reason of seemingly high NUE of cropping systems in Ukraine was in reality attributed to high N mineralization rates in organic-reach Ukrainian Black soils (2024a, Bilanchyn *et al* 2021) and in a lesser extent to additional N inputs (total atmospheric N deposition, biological N fixation, N in irrigation waters, N in crop residues) currently unaccounted in the 'classic' N-Calculator approach developed by Leach *et al* (2012). To enhance the accuracy of crop VNFs, we propose an advanced 'budget' N-Calculator approach that considers additional N sources potentially available for crops, beyond just N fertilizers. This approach might be potentially valuable for regions/ countries (i) exposed to a high atmospheric N deposition (e.g. Asian countries or specific N polluted regions), (ii) with a high N content in irrigation water (e.g. Portugal; Serra *et al* 2023), (iii) applying crop residues back to the field and (iv) with low N inputs struggling on soil N-mining (e.g. Eastern Europe, South Africa; Elrys *et al* 2021, Bilanchyn *et al* 2021). However, the latter option seems to be quite challenging to be realized for the main crop categories at a country scale. Firstly, due to data availability—to estimate N mineralization for certain cropping system in a certain soil under certain pedoclimatic conditions, control (no fertilizer) and treatment (fertilized) plots are needed (Serra *et al* 2022). Secondly, because NUE and a net N-mineralization rate are suggested to be quantified for an entire crop rotation cycle rather than for an individual crop to avoid over-under-estimation (Quemada *et al* 2020). Thirdly, the new budget VNF results would not be comparable with previously published ones using the 'classic' N-Calculator. Therefore, we suppose that the 'budget' approach will be of use for targeted research to estimate and compare the impact of additional N inputs on crop VNFs and food NF in sensitive countries/ regions/ areas.

The VNFs for pork and beef production were shown to be high compared to most countries but were comparable with those of Japan (Shibata *et al* 2014, table S4). This can likely be a combined result of two aspects. First, technologically these livestock subsectors were not very well updated in Ukraine due to increasing debt and lack of investments (Kravchenko *et al* 2020) and thus low NUEs in swine and cattle husbandry are expected to be in place. Second, we assumed that all animal products consumed by Ukrainians were produced domestically (as import/ export data were not available at a required level). This may slightly overestimate real N losses from these categories. At the same time, VNFs for poultry, diary and eggs production were in the middle of ranges for developed countries indicating their higher level of technological development and NUE compared to beef and pork production (table S4 and references therein). It is noteworthy, unlike most other studies used a complete bottom-up approach (N-calculator; see Leach *et al* 2012), we partially followed the top-down approach of Shindo and Yanagawa (2017) based on Smil (2000) to calculate NCE. We divided NCE by N meat-to-live weight ratio to derive feed NCE, which further was used for VNF calculations using a N-Calculator tool.

In addition, poor or often practically absent manure management in Ukraine, where only 10% is recycled (2024a), made animal production even more environmentally harmful. Considering the average manure excretion rates for Eastern Europe (IPCC 2006, Velthof 2014), our assessment revealed that the wasted manure in the livestock sector could contribute to a massive additional production footprint of 23.3 kg N cap^{-1} yr^{-1} (table S6). This might double the total per capita NF in Ukraine from 22.1 to 44.8 kg N yr^{-1} making it one of the biggest currently estimated in the globe with >92% share of food component.

The gross actual food N consumption footprint (before WWT applied) is quite uniform (5–6 kg N cap^{-1} yr^{-1}; figure 2) across developed countries (*e.g.* Leach *et al* 2012, Pierer *et al* 2014, Liang *et al* 2016), slightly lower in Ukraine (4.1 kg N cap^{-1} yr^{-1}) and supposedly in other non-EU Eastern European countries, but typically much lower (2–2.6 kg N cap^{-1} yr^{-1}) in developing countries (*e.g.* in Sub-Saharan Africa; Hutton *et al* 2017, Elrys *et al* 2021) which struggle of undernutrition (Elrys *et al* 2021). We cross-checked this component of Ukrainian NF based on an 'incoming N flux', a consumed N food amount estimated by FAO (2023), quantified by the N-Calculator approach with an 'outgoing N flux', an excreted N amount assessed using medically approved excretion rates for a healthy adult (MHU 2023). We found that consumed-food-derived NF (4.1 kg N cap^{-1} yr^{-1}) was close to a lower limit of an excretion rates (4.3–6.8 kg N yr^{-1}) adopted in Ukraine by MHU (2023) and coincided well with an average estimate of 4.7 kg N cap^{-1} yr^{-1} (range: 1.4–13.4 kg N cap^{-1} yr^{-1}) summarized by Rose *et al* (2015). This is in line with a concept of zero N food balance (equilibrium) to be achieved by a healthy adult under a moderate physical activity (WHO/FAO/UNU 2007). However, these average estimates do not mean that the protein N consumption and physiological N excretion were equally distributed across a local population in Ukraine. E.g. according to the Global Nutrition Report (GNR 2023) around 27.5% and 24.5% of adult women and men, respectively, were living with obesity in Ukraine as of 2016.

4.2. Options for sustainable healthy diets

On the topic on food consumption, it is important to note that minimum levels of protein intake or Reference Nutrient Intake (RNI) rates for proteins or Recommended Dietary Allowance (RDA) have been under debate since they were firstly introduced (Wu 2016). Despite this, those recommended rates are regularly updated by WHO/ FAO/ UNU (2007), European Food Safety Authority (EFSA 2012) and the corresponding authorities of developed countries (USDA 2020, NNR 2023, NRV 2023), and currently range from 2.6–2.9 kg N cap^{-1} yr^{-1} for adult women and 2.9–3.2 for adult men (table S7). Whereas, excretion rates, which seem to be more 'dogmatic' as they often refer to data of >20–50 year studies, should definitely be revised too to support updated RNIs/ RDAs. E.g. MHU (2023) still referred to 'excretion' standards developed in the former Soviet Union, while many studies in a review of Rose *et al* (2015) were dated on 1970s–90s.

By assuming the equal distribution of women and men globally and considering Ukraine as an integral part of the Europe (EU) we further consider a

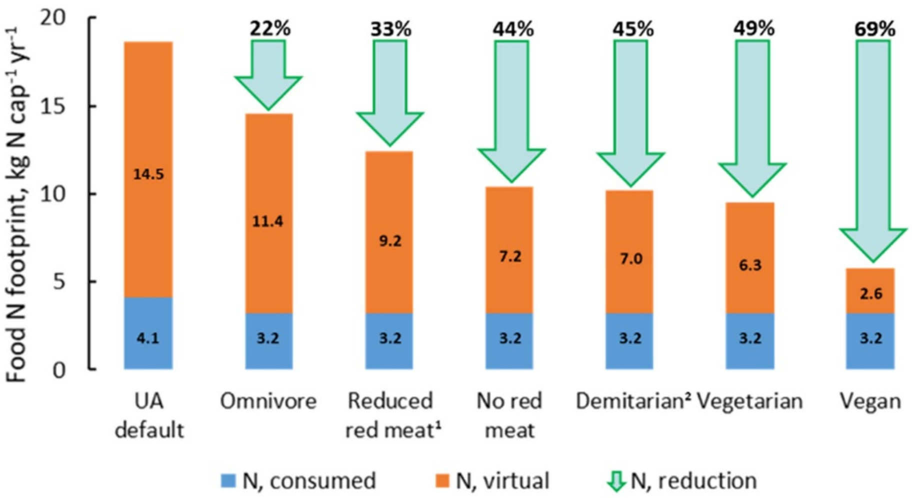

Figure 3. Comparison of food N footprints of a default protein diet in Ukraine as of 2017 and five suggested more sustainable healthy diets utilizing reduced protein intake according to EFSA (2012) and WHO/ FAO/ UNU (2007) recommendations [UA default: a diet of an average Ukrainian according this study results; see text S1 for detailed information on each suggested diet; [1]exclusion of beef, lamb and goat meat from the diet; [2]50% reduction of all animal products in the diet].

recommended (gross) actual food N consumption for a healthy adult (age of 18–50 years) to be equal to 3.2 kg N cap^{-1} yr^{-1} (EFSA 2012) rather than outdated higher rates re-approved by the Ministry of Health of Ukraine in 2017 (MHU 2017). We suppose that the essential step for an average Ukrainian towards healthier diet is to decrease N intake to the EU minimum level, which also reduces an individual environmental NF. However, an individual NF is not solely dependent on the amount of protein consumed but also on the types of protein products consumed, as larger nitrogen losses occur throughout the production chain (Galloway *et al* 2014). Given this, we estimated six types of proposed diets all with 3.2 kg N cap^{-1} yr^{-1} protein consumption (figure 3, text S1 and table S7) in order to show evidence for how and to what extent personal choice of healthy food can be a win–win approach to sustain the environment we are living in.

A proposed omnivore diet with an equal reduction of protein intake across all food categories from 4.1 to 3.2 kg N cap^{-1} yr^{-1} to meet the minimum level of protein consumption decreases the food NF by 22%. Further on, refusal to eat beef and lamb leads to 6.2 kg N (33%) decrease from a default diet, while refusal to all red meat diminishes a personal food footprint by 8.2 kg N (44%) annually. The demitarian diet, conceptualized by Westhoek *et al* (2015), proposes a 50% reduction in the consumption of all types of animal products; this leads to 45% decrease (8.4 kg N cap^{-1} yr^{-1}) of a food NF. Not surprisingly, vegetarian and vegan diets are more environmentally sustainable lowering default food footprint by 49 and 69% respectively (figure 3). Bearing in mind a current amount of manure-wasted in Ukrainian livestock sector (2024a), the environmental benefit of even a slight protein intake reduction per capita and/or gradual swapping out to any of proposed or similar diets will be more than crucial (table S8). Of course, it does not mean that locals by changing their diets have to counterpart fundamental drawbacks and underregulation legacy in Ukrainian agricultural sector, which is the responsibility of the corresponding governmental authorities (Kravchenko *et al* 2020). But we suggest this might be an additional incentive to switch to a healthier diet and simultaneously raise public awareness on sustainable food production and existing barriers (Scarborough *et al* 2023).

Furthermore, opportunities to reduce food waste and associated N losses exist throughout the food supply chain (UNEP 2021). By identifying markets for by-products and sub-standard products during processing and packaging, waste can be reduced. Consumption of locally produced products or improved storage infrastructure and transportation can help minimize losses during distribution. Stringent quality standards for crops and safety often result in the disposal of perfectly safe products. Expanding the utilization of food products can be achieved by finding alternative markets for 'ugly crops' and recycling them in livestock systems, as well as providing public training in safe food handling practices. Consumer-level food waste is the largest category, accounting for up to 17% of the global food supply (UNEP 2021). To address this, public outreach and education initiatives are needed.

In this regard, the online N-Calculator is a very useful tool for individuals to (i) quantify their current footprint (impact) on environment with their everyday-life pattern of resource use and (ii) estimate how alterations in food preferences, household energy and transport use can decrease their NF (Galloway *et al* 2014). The fully operated Ukrainian version (https://n-print.org) has been recently launched based on current study results and questionnaire surveys conducted within the UNEP-GEF Towards INMS project.

4.3. War impact on NF and associated N pollution

Although, this study covered the year of 2017 and was begun before the war in Ukraine, we cannot help but briefly touch the influence of this devastating act against the peaceful Ukrainian nation on an individual NF and associated N loads to the environment.

The large-scale invasion by Russia that began on February 24, 2022 had a profound impact on and severely disrupted the entirety of Ukraine, leading to civilian casualties, extensive damage to infrastructure and facilities, as well as the destruction of various critical storages including fuel, raw materials, stock, and food supplies (Guenette *et al* 2022, Pereira *et al* 2022). A massive flow of refugees from mostly affected/occupied areas to western regions of Ukraine or abroad resulted in the skewed redistribution of N loads associated with individual NFs across country. Around 20% of population (*ca.* 8 mln persons) left the Ukraine and so far, remained abroad as refugees (OporaUA 2023), reducing a country-wide personal NF by 177 Gg N yr^{-1}. Whilst the amount of internally displaced people mainly to western and central regions of Ukraine was accounted to be 4.9 mln people (OporaUA 2023) with a combined NF of 108 Gg N yr^{-1}. Such a large flow of the forced migration coupled with massive relocated of businesses to less affected regions overloaded their largely outdated (and not designed for such amounts) civilian infrastructure (including WWTP and landfill facilities, transportation, energy system etc) leading to higher N losses from households and increasing N load density per certain area to the environment (which has never exposed by such a N pressure for a long-term). We suggest that on average **food consumption NF** largely remained in the similar ranges or slightly increased due to poorer waste management. **Food production NF** might have increased via VNF increases for local products due to product/crop damages (through military operations) before distribution and poorer waste/residue management upon production chain. We expect a reduction of **transport NF** during the war considering individual movement limitation due to imposition of curfews, transportation restrictions (in some regions) and gasoline shortages (in the initial months and time to time afterwards). Households across the country experienced in regular (and often prolong) blackout periods caused by attacks on power-generating facilities, redirection power from undamaged facilities to support critical infrastructure (hospitals, water supply, central heating supply, industry etc) and to avoid overloading of vulnerable power systems. Therefore, a reduction of individual **energy NFs** was in place.

We anticipate a further increase of N loads in less affected regions (located in the rear) during the ongoing war period via the overconcentration of people seeking asylum, overpressure for regional infrastructure and less controlled industrial pollution of recovered/ relocated businesses. Undoubtedly, the intensive post-war renovation in Ukraine will also significantly raise N loads, including individual NFs, above pre-war levels (Medinets *et al* 2020a, 2020b, 2021, Skiba *et al* 2021), necessitating sustained efforts to mitigate N emissions and safeguard the environment.

5. Conclusions

The first ever calculated per capita NF in Ukraine clearly highlighted the most critical components (food production chain, food consumption pattern, the efficacy of WWTP, connection to WWT system) and outlined specific challenges that are hard to address (data availability, soil N-mining, manure wastes). We emphasized that the seemingly high NUE of cropping systems in Ukraine was, in fact, mirrored by the high N mineralization rate in Ukrainian soils with high organic matter content. We showed how 'a personal choice' can make a big difference. Healthier and more sustainable diets were proposed as targeted options capable of achieving substantial reductions in an individual's 'default' food NF by at least 22% (omnivore), 33% (reduced red meat), 44% (no red meat), 45% (demitarian), 49% (vegetarian) and 69% (vegan). We emphasize that the actual food NF reduction could be significantly higher if the wasted N manure is taken into account. Although the average Ukrainian has a moderate personal footprint in terms of housing and transportation, a set of approved mitigating measures has been suggested.

To estimate one's current personal footprint (total and by category), clearly visualize the impact of consumption changes and to further monitor personal progress towards mitigation, the recently launched Ukrainian version of the online N-Calculator is available online for use (https://n-print.org).

The impact of the war is expected to either result in a slight increase or no change in individual food consumption NFs and is likely to lead to an increase in food production NFs for local products. Concurrently, reductions in individual transport and energy NFs were likely experienced across Ukraine. Nevertheless, the mass displacement of refugees to less affected regions has caused substantial strain on the predominantly outdated civilian infrastructure, resulting in higher N losses (as a combined NF) and consequently exacerbating the N load on the environment.

In the longer-term, following Ukraine's glorious victory international and governmental support, capital investments, legislative improvement and regulations are crucial to further diminish an individual NF in Ukraine by increasing NUE in agricultural sector, establishing manure management system, improving

WWT facilities, promoting renewable energy systems, developing required infrastructure.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

This study was facilitated by N-print team (https://n-print.org), supported by the GEF-UNEP funded project 'Towards INMS' (see www.inms.international) and the Researcher at Risk Fellowship Program of the British Academy with the Council for At-Risk Academics (CARA). Also, we are grateful to all respondents who completed their surveys.

Ethical statement

There are no ethical concerns regarding this data analysis.

ORCID iDs

Sergiy Medinets https://orcid.org/0000-0001-5980-1054
Allison M Leach https://orcid.org/0000-0003-0171-1405
Tetiana Pavlik https://orcid.org/0009-0008-6745-5890
Volodymyr Medinets https://orcid.org/0000-0001-7543-7504
James N Galloway https://orcid.org/0000-0001-7676-8698

References

Abrahams Z, Mchiza Z and Steyn N P 2011 Diet and mortality rates in Sub-Saharan Africa: stages in the nutrition transition *BMC Public Health* **11** 1–12

Amatuni L, Ottelin J, Steubing B and Mogollón J M 2020 Does car sharing reduce greenhouse gas emissions? Assessing the modal shift and lifetime shift rebound effects from a life cycle perspective *J. Cleaner Prod.* **266** 121869

Bilanchyn Y, Tsurkan O, Tortyk M, Medinets V, Buyanovskiy A, Soltys I and Medinets S 2021 Post-irrigation state of black soils in South-Western Ukraine *Regenerative Agriculture* ed D Dent and B Boincean (Springer) (https://doi.org/10.1007/978-3-030-72224-1_27)

Biresselioglu M E, Kaplan M D and Yilmaz B K 2018 Electric mobility in Europe: a comprehensive review of motivators and barriers in decision making processes *Transp. Res.* A **109** 1–13

Buehler R, Pucher J, Gerike R and Götschi T 2017 Reducing car dependence in the heart of Europe: lessons from Germany, Austria, and Switzerland *Transp. Rev.* **37** 4–28

CBS 2018 Centraal bureau voor de statistiek—statistics Netherlands (available at: www.cbs.nl/en-gb)

Dhar A R, Oita A and Matsubae K 2021 The effect of religious dietary cultures on food nitrogen and phosphorus footprints: a case study of India *Nutrients* **13** 1926

Di Girolamo F G *et al* 2017 Higher protein intake is associated with improved muscle strength in elite senior athletes *Nutrition* **42** 82–86

Dolina L F 2011 *Wastewater Treatment from Biogenic Elements* (Kontinent) p 198

EFSA 2012 European food safety authority, scientific opinion on dietary reference values for protein *EFSA J.* **10** 2557

Einarsson R and Cederberg C 2019 Is the nitrogen footprint fit for purpose? An assessment of models and proposed uses *J. Environ. Manage.* **240** 198–208

Einarsson R, Henriksson M, Hoffmann M and Cederberg C 2022 The nitrogen footprint of Swedish food consumption *Environ. Res. Lett.* **17** 104030

Elrys A S, Desoky E M, Alnaimy M A, Zhang H, Zhang J, Cai Z and Cheng Y 2021 The food nitrogen footprint for African countries under fertilized and unfertilized farms *J. Environ. Manage.* **279** 111599

Ember 2022 *Global Electricity Review* (available at: https://ember-climate.org/insights/research/global-electricity-review-2022/)

FAO 2023 Food balances. FAOStat. food and agriculture organization of the UN (available at: www.fao.org/faostat/en/#data/FBS)

Galloway J N *et al* 2007 International trade in meat—the tip of the pork chop *Ambio* **36** 622–9

Galloway J N, Bleeker A and Erisman J W 2021 The human creation and use of reactive nitrogen: a global and regional perspective *Annu. Rev. Environ. Resour.* **46** 255–88

Galloway J N and Cowling E B 2021 Reflections on 200 years of Nitrogen, 20 years later: this article belongs to Ambio's 50th Anniversary Collection. Theme: eutrophication *Ambio* **50** 745–9

Galloway J N, Winiwarter W, Leip A, Leach A M, Bleeker A and Erisman J W 2014 Nitrogen footprints: past, present and future *Environ. Res. Lett.* **9** 115003

GECO 2022 Global energy and climate outlook 2022: energy trade in a decarbonised world *JRC Science for Policy Report* (available at: https://publications.jrc.ec.europa.eu/repository/handle/JRC131864)

GNR 2023 Nutrition profile for Ukraine *Global Nutrition Report* (available at: https://globalnutritionreport.org/resources/nutrition-profiles/europe/eastern-europe/ukraine/)

Gonçalves V M P 2013 Impact of Nitrogen into the Environment. A Step on Nitrogen Footprint Calculation in Lisbon, Portugal *Doctoral Dissertation* Universidade de Lisboa Portugal

Guenette J D, Kenworthy P G and Wheeler C M 2022 Implications of the War in Ukraine for the Global Economy EFI Policy Note 3 (World Bank Group)

Gustavsson J *et al* 2011 Global food losses and food waste–Extent, causes and prevention. Food and agriculture organization of the UN SAVE FOOD: An initiative on food loss and waste reduction, *9* p 2011

Heinrichs H 2013 Sharing economy: a potential new pathway to sustainability *GAIA* **22** 228–31

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

IEO 2021 The International Energy Outlook (IEO) (Center for Strategic and International Studies. U.S. Energy Information Administration) (available at: www.eia.gov/outlooks/ieo/)

IPCC 2006 IPCC guidelines for national greenhouse gas inventories volume 4: agriculture, forestry and other land use (available at: www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf)

Kovalova N V, Medinets V I and Medinets S V 2021 Peculiarities of long-term changes in bacterioplankton numbers in the Dniester liman *Hydrobiol. J.* **57** 27–36

Kovalova N, Medinets S, Konareva O and Medinets V 2010 Long-term changes of bacterioplankton and chlorophyll a as indicators of changes of north-western part of the black sea ecosystem during the last 30 years *J. Environ. Prot. Ecol.* **11** 191–8

Kravchenko O, Kucher A, Hełdak M, Kucher L and Wysmułek J 2020 Socio-economic transformations in Ukraine towards the sustainable development of agriculture *Sustainability* **12** 5441

Leach A M, Cattell Noll L, Atwell B, Cattaneo L R and Galloway J N The nitrogen footprint of food production in the United States (in preparation)

Leach A M, Galloway J N, Bleeker A, Erisman J W, Kohn R and Kitzes 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

Maughan R J, Greenhaff P L and Hespel P 2013 Dietary protein for athletes: from requirements to optimum adaptation *Food, Nutrition and Sports Performance III* (Routledge) ch 6

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

Medinets S *et al* 2020a Assessment of riverine loads of nitrogen and phosphorus to the Dniester Estuary and the Black Sea over 2010–2019 *Monitoring of Geological Processes and Ecological Condition of the Environment* (EAGE) (https://doi.org/10.3997/2214-4609.202056029)

Medinets S *et al* 2020b Rates of atmospheric nitrogen deposition to agricultural and natural lands within the lower Dniester catchment *Monitoring of Geological Processes and Ecological Condition of the Environment* (EAGE) (https://doi.org/10.3997/2214-4609.202056053)

Medinets S *et al* 2024b Atmospheric deposition of nitrogen and sulphur in the Dniester catchment: the impact of war at a glance *Int. J. Environ. Stud.* **81** accepted

Medinets S *et al* 2024a Assessment of nitrogen flows, impacts and solutions in East Europe *The International Nitrogen Assessment* (Cambridge University Press) accepted

Medinets S, Gasche R, Skiba U, Medinets V and Butterbach-Bahl K 2016 The impact of management and climate on soil nitric oxide fluxes from arable land in the Southern Ukraine *Atmos. Environ.* **137** 113–26

Medinets S, Kovalova N, Mileva A, Konareva O, Gazyetov Ye, Soltys I, Pitsyk V and Medinets V 2021 Fluxes of reactive nitrogen and greenhouse gases from arable land in South-Western Ukraine *Regenerative Agriculture* ed D Dent and B Boincean (Springer) (https://doi.org/10.1007/978-3-030-72224-1_20)

Medinets S, Skiba U, Rennenberg H and Butterbach-Bahl K 2015 A review of soil NO transformation: associated processes and possible physiological significance on organisms *Soil Biol. Biochem.* **80** 92–117

MHU 2017 The order on the approval of the norms of physiological needs of the population of Ukraine in basic food substances and energy (Ministry of Health of Ukraine) (available at: https://zakon.rada.gov.ua/laws/show/z1206-17?lang=en#Text)

MHU 2023 Ministry of Health of Ukraine (available at: https://en.moz.gov.ua/)

NNR 2023 Nordic nutrition recommendations 2023. Nordic council of ministers (available at: https://pub.norden.org/nord2023-003/appendix.html)

NRV 2023 Nutrient reference values for Australia and New Zealand (available at: www.eatforhealth.gov.au/nutrient-reference-values/nutrients/protein)

Obiero K, Meulenbroek P, Drexler S, Dagne A, Akoll P, Odong R, Kaunda-Arara B and Waidbacher H 2019 The contribution of fish to food and nutrition security in Eastern Africa: emerging trends and future outlooks *Sustainability* **11** 1636

OporaUA 2023 The impact of a full-scale war on the migration of Ukrainian people: how the scale of displacement is assessed by the state of Ukraine and international organizations *Media release at OporaUA.org* (available at: www.oporaua.org/en/viyna/24523-vpliv-povnomasshtabnoyi-viini-na-migratsiiu-ukrayintsiv-iak-masshtabi-peremishchennia-otsiniuiut-derzhava-ukrayina-ta-mizhnarodni-organizatsiyi-24523)

Pereira P, Zhao W, Symochko L, Inacio M, Bogunovic I and Barcelo D 2022 The Russian-Ukrainian armed conflict impact will push back the sustainable development goals *Geogr. Sustain.* **3** 277–87

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** 128–36

Quemada M, Lassaletta L and Jensen L S 2020 Exploring nitrogen indicators of farm performance among farm types across several European case studies *Agric. Syst.* **177** 102689

Renewal 2022 Draft Plan for the renewal of Ukraine Materials of the working group "Housing, living, modernization of cities and regions of Ukraine *National Council for Innovation of Ukraine after the war of the Cabinet of Ministers of Ukraine* p 350 (available at: www.kmu.gov.ua/storage/app/sites/1/recoveryrada/ua/construction-urban-planning-modernization-of-cities-and-regions.pdf)

Rose C, Parker A, Jefferson B and Cartnell E 2015 The characterization of feces and urine: a review of the literature to inform advanced treatment technology *Crit Rev. Environ. Sci. Technol.* **45** 1827–79

Rozenberg J and Fay M 2019 Beyond the gap: how countries can afford the infrastructure they need while protecting the planet. Sustainable infrastructure *World Bank Report* (World Bank Group) (available at: https://openknowledge.worldbank.org/handle/10986/31291)

SAEE 2021 Report on the Promotion and Use of Energy from Renewable Sources in Ukraine in 2019–2020 *State Agency for Energy-efficiency and Energy-saving* (available at: https://saee.gov.ua/sites/default/files/blocks/Report%20RES%202019-2020_eng%2013.12.2021_0.pdf)

Scarborough P *et al* 2023 Vegans, vegetarians, fish-eaters and meat-eaters in the UK show discrepant environmental impacts *Nat. Food* **4** 1–10

Serra J, Medinets S, Lassaletta L, Zhang X, Boincean B and Aguilera E 2022 Missing inputs and outputs *Guidance Document on Nitrogen Use Efficiency Methodology for Different Purposes* ed L Lassaletta and A Sanz-Cobena (INMS)

Serra J, Paredes P and Cordovil C 2023 Is irrigation water an overlooked source of nitrogen in agriculture? *Agric. Water Manage.* **278** 108147

Shibata H *et al* 2017 Nitrogen footprints: regional realities and options to reduce nitrogen loss to the environment *Ambio* **46** 129–42

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

Shindo J and Yanagawa A 2017 Top-down approach to estimating the nitrogen footprint of food in Japan *Ecol. Indica* **78** 502–11

Sieminski A 2015 Annual energy outlook 2015 (US Energy Information Administration)

Skiba U, Medinets S, Cardenas L M, Carnell E J, Hutchings N J and Amon B 2021 Assessing the contribution of soil NO_x emissions to European atmospheric pollution *Environ. Res. Lett.* **16** 025009

Smil V 2000 *Feeding the World: A Challenge for the Twenty-First Century* (MITPress) pp 388

Smil V 2002a Nitrogen and food production: proteins for human diets *AMBIO* **31** 126–31

Smil V 2002b Worldwide transformation of diets, burdens of meat production and opportunities for novel food proteins *Enzyme Microb. Technol.* **30** 305–11

SSSU 2018 Statistical yearbook of Ukraine for 2017 (State Statistics Service of Ukraine) (available at: https://ukrstat.gov.ua/druk/publicat/kat_u/2018/zb/11/zb_seu2017_e.pdf)

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

Sutton M A, Dragosits U, Tang Y S and Fowler D 2000 Ammonia emissions from non-agricultural sources in the UK *Atmos. Environ.* **34** 855–69

Sutton M A, Howard C H and Erisman J W 2011 *The European Nitrogen Assessment* (Cambridge University Press)

Sutton M A, Howard C M and Mason K E 2022 *Nitrogen Opportunities for Agriculture, Food & Environment. UNECE Guidance Document on Integrated Sustainable Nitrogen Management* (UK Centre for Ecology & Hydrology)

Themen D 2013 Losses and waste in Ukraine. Country Report *UN Food and Agrilculture Organization* (available at: www.fao.org/3/a-au825e.pdf)

Tsurkan O, Bilanchyn Y, Medinets V, Soltys I and Medinets S 2021 Effects of drip irrigation on the composition and fertility of Black Soils in Odesa Region *Regenerative Agriculture* ed D Dent and B Boincean (Springer) (https://doi.org/10.1007/978-3-030-72224-1_28)

Tuchkovenko Yu S, Sapko Yu O and Tuchkovenko O A 2020 Description of biological wastewater treatment plants of city of Odesa as sources of marine environment pollution in current period *Ukr. Hydrometeorol. J.* **25** 127–35

UNEP 2021 Food Waste Index Report 2021 (United Nation Environmental Programme) p 100

USDA 2020 Dietary Guidelines for Americans (available at: www.dietaryguidelines.gov/sites/default/files/2020-12/Dietary_Guidelines_for_Americans_2020-2025.pdf)

Van Dijk M, Morley T, Rau M L and Saghai Y 2021 A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050 *Nat. Food* **2** 494–501

Velthof G L 2014 Report Task 1 of Methodological studies in the field of Agro-Environmental Indicators. Lot 1 excretion factors *Final draft. Alterra. Wageningen* p 73 (available at: https://ec.europa.eu/eurostat/documents/2393397/8259002/LiveDate_2014_Task1.pdf/e1ac8f30-3c76-4a61-b607-de99f98fc7cd)

Westhoek H, Lesschen J P and Leip A 2015 Nitrogen on the Table: the influence of food choices on nitrogen emissions and the European environment (European Nitrogen Assessment Special Report on Nitrogen and Food) Centre for Ecology & Hydrology

WHO/ FAO/ UNU 2007 World health organization/ food and agriculture organization/ united nations university, protein and amino acid requirements in human nutrition; Report of a joint FAO/WHO/UNU expert consultation technical report series No 935 (WHO)

WHO 2019 *Progress on Household Drinking Water, Sanitation and Hygiene 2000–2017. Special Focus on Inequalities* (United Nations Children's Fund (UNICEF) and World Health Organization (WHO))

Wu G 2016 Dietary protein intake and human health *Food Funct.* **7** 1251–65