The impact of nutrient-rich food choices on agricultural water-use efficiency

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When distributed equally, the total amount of food produced worldwide could sufficiently meet current global demand. Still, malnutrition in the form of nutrient deficiencies continues to prevail in both low- and high-income countries. At the same time, natural resource use for agriculture is reaching or exceeding environmental boundaries. By integrating a comprehensive micronutrient scoring method with data on agricultural water demand, this analysis aims to re-evaluate the global water-use efficiency of dietary nutrient production. A stronger reliance on more nutrient-dense foods could lead to higher water-use efficiencies, though dietary water footprints were likely to increase overall. With a more detailed focus on plant and animal foods, we find that most dietary protein sources show comparable water-use efficiencies, and thus can be drivers for agricultural water demand. Animal foods, besides having a unique nutrient profile, often do not compete directly with crops for the same water resources. However, a significant reduction in the demand for utilizable freshwater resources could be achieved by reducing the amount of feed crops in ruminant diets.

Freshwater resources are of fundamental importance for global food production. Besides land and energy input, freshwater supply directly determines the efficiency with which the agricultural sector is able to produce food for human consumption. Currently, large parts of the world do not have access to sufficient water resources[1]. Conditions could worsen over the coming decades as climate change is expected to lead to a physical decrease in regional water availability for humans; water scarcity, at least seasonally, might also extend to regions that are currently showing abundant water resources. With agriculture being responsible for about 70% of global freshwater use[2], and many world regions already facing water resource limitations, an efficient use of restricted water resources is critical to ensure sufficient food production. Since the global agricultural system is either reaching or regionally already exceeding its limits of sustainable natural resource use—water being one of them—new approaches are required to ensure that future food demand can be met. In this context, changing dietary preferences and guidance could significantly impact the environmental sustainability of agriculture.

When distributed equally, the total amount of food that is being produced today could sufficiently meet current global caloric and protein demands[3]. While economic and cultural barriers are the primary reasons for malnourishment in many world regions, inadequate supplies of essential nutrients in diets have been observed in both low- and high-income countries. Besides protein, some of the world's most common nutrient deficiencies include iron, zinc, iodine, selenium, and vitamins A, B_6, and B_{12}. While some nutrients such as vitamin A and iodine show clear regional patterns, mostly affecting populations in low-income countries, others such as iron or vitamin B_{12} can be found globally, mostly within specific, predominantly more vulnerable groups of the population[4–8]. These circumstances lead to the assumption that current average dietary patterns do not provide sufficient nutrition for large parts of the population. Inadequate micronutrient intake increases both the risk for infectious disease due to suppressed immune system functioning, as well as non-communicable diseases, including anaemia, cardiovascular disease, thyroid disorders, and cancer[9–12]. The total (long-term) implications and contributions of nutrient deficiencies to health are hard to estimate because they are often intertwined with other lifestyle and environmental factors. Changes in consumer demands towards more nutrient-dense foods could be one out of several important steps for reversing this trend by improving both nutritional and environmental health.

In light of worldwide prevalent nutrient deficiencies and expected decreasing freshwater availability, the aim of this study is to re-examine the global water productivity of agriculture from a more detailed nutritional perspective, and to explore options towards higher water-use efficiencies and potentially water savings. In a first step, we link required freshwater inputs for food production to the micronutrient contents of specific foods, using them as an indicator of their nutritional value. We start our analysis by comparing the average total and consumptive global water use for 24 foods and their respective content of 22 essential micronutrients. In a second step, we assess water-use efficiencies of different protein sources, combining several indicators for their nutritional value. Finally, we discuss the possibilities for water use reduction in the agricultural sector from the demand side.

Calculating the water demand of food production

A number of studies have estimated the water demand for food production. Consistent with most research on land use and greenhouse gas (GHG) emissions from agriculture, previous research has focused primarily on the amount of food (or protein) produced per unit of freshwater on a weight or caloric basis, that is, how many litres of water are required to produce 1 kg of food[13–15]. Global modelling approaches on agricultural water demand include WATERSIM, LPJmL, the GEPIC model, the IMPACT model, and the Water Footprint Network[16–20]. The latter is the only modelling approach that includes livestock data. These models distinguish regionally specific needs for rain and irrigation/processing water, also referred to as green and blue water, respectively. Generally projected rising water demands are mainly due to increasing food demands, and

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are typically evaluated with regard to the caloric values of foods. Besides data stemming from global modelling approaches, life cycle assessments play an important role for evaluating the sustainability of foods with regard to their local water demand. Based on whole foods or dietary pattern analyses, research more recently began to integrate food quality markers to increase the comparability of foods showing large nutritional variability. Often, those assessments are part of a comprehensive environmental impact assessment also including GHG emissions, land use, and air acidification[21–24]. While studies comparing single foods conclusively found that animal products, especially pork and beef, yield the largest water demand, plant foods, such as cereals and legumes consume lower amounts of water either per unit weight or kilocalorie (kcal) produced. In the context of entire dietary patterns, it appears that besides animal products, fruit, vegetables, and nuts and seeds can be drivers for the overall water demand for food production, suggesting a mismatch when aiming at both a higher intake and diversity of nutrient-rich foods, and minimizing the environmental impacts of agriculture. Consequently, the next necessary step for environmental impact research on food production is the inclusion of more detailed nutritional analyses. So far, a few studies undertook a simultaneous quantitative investigation of the nutritional value of specific foods and their environmental impact, in particular their GHG emissions[25–28]. In line with the research outlined in the previous section, animal products generally show considerably higher carbon footprints than plant foods.

Summarizing existing research on the sustainability of food production, it becomes clear that over the last years more and more studies shifted their focus from pure food quantities towards dietary quality and most recently nutritional quality of foods (amounts and shares of various macronutrients and micronutrients) in relation to their environmental impact. Several different nutrient density scoring methods were applied when assessing the nutritional quality of foods; this makes a comprehensive comparison difficult. Some of these methods show certain limitations, for example, when indices are calculated solely for foods in raw, uncooked forms. Depending on the specific type of food, for example, cereals, this might be an inedible state. Some nutrient scores limit the amount of nutrients to a small number and have only been applied in regional contexts. Larger-scale as well as more comprehensive research, from both a natural resource use and nutritional perspective, is hence the next necessary step for investigating the links between environmental and nutritional sustainability in the global food system.

Results

water-use efficiency of global nutrient production. While previous analyses estimated the water-use efficiency of food products on a global level by comparing food groups on a weight or caloric basis, our work integrates the nutritional value of food using a comprehensive nutrient scoring method. Figure 1 presents the results of our baseline analysis regarding the mineral and vitamin content of all main food groups as categorized by the Food and Agriculture Organization (FAO). It ranks foods according to nutrient content scores (NCS) per gram net weight, that is, the sum of the recommended dietary allowances (RDAs) as the percentage of each nutrient. These values are presented in relation to the overall protein and caloric content of these foods in the background. Offal, seafood, legumes, chicken eggs, and vegetables rank highest in overall nutrient content, while major cereals, fruit, oils and fats, and sugar show the lowest NCS. Muscle and organ meats are inherently produced together in an average ratio of 70% muscle meat and 30% offal such as heart, liver, and kidneys[29]. When combining the average scores from muscle and organ meats, meat ranks second after shellfish. These scores illustrate only overall protein and micronutrient contents, not the biological value or bioavailability of those nutrients. Specific nutrient distribution can vary largely between food groups.

Combining the data from Fig. 1 with the overall water use for food production allows ranking of those foods according to their water-use efficiency. Figure 2 depicts the global water-use averages for main food groups, which are displayed from the highest to the lowest water-use efficiency. NCS are shown per litre net water use (NCS l^{-1}), that is, added green and blue water scores. In the background, the dark blue outlined bars depict the consumptive share of (blue) water demand per litre for each food group. Vegetables and starchy roots show the highest overall efficiencies with broad mineral and vitamin distributions. Starchy roots also show low consumptive water-use rates. Cereals rank comparatively high with scores between 1.09 and 2.04 NCS l^{-1}. Combining the average scores from muscle and organ meats, meat would rank ninth, between wheat and eggs, with a score of 1.45 NCS l^{-1} total water use. Both soybeans and other legumes (beans, peas, lentils, groundnuts) rank high on this scale and show low consumptive water-use rates. Fats, both of animal and plant origin (soybean, sunflower, groundnut, rapeseed, sesame, palm, coconut, olive oil), rank low.

Our analysis makes it possible to evaluate various food groups on a more differentiated level when water use poses a concern for agricultural resource demand. In areas with sufficient freshwater availability, the production of the most nutrient-rich foods as listed in Fig. 2 would not be hindered by environmental water quantity concerns. Hence, the general application of these findings depends on actual regional water availability, the share of imported foods, and the nutritional status of the local population, so that the specific focus of nutrition-sensitive approaches to agriculture might shift according to regional factors. Supplementary Figs. 3–5 display NCS and associated water-use efficiency with regard to a set of 11 nutrients out of the total of 22, which show a higher prevalence of deficiencies in populations worldwide, including high-income countries. This particular focus leads to smaller changes in the rankings of food groups, with mostly animal foods ranking slightly higher due to their combined higher average concentrations of iron, zinc, and vitamins A and B_{12} (as well as calcium from dairy).

Dietary context. The total water footprint of different dietary patterns can vary largely depending on its specific composition. There are many options to structure a healthy diet, that is, a diet that sufficiently meets the macronutrient and micronutrients demand of an individual. Origin, amount, variety and composition of foods within omnivorous or solely plant-based diets can differ immensely within each dietary pattern, which also depends on personal needs, accessibility, and preferences. This limits the ability to compare different dietary patterns without a large amount of generalization. Supplementary Fig. 6a–d presents the micronutrient profiles and water demand of 100 kcal servings of each major food group. This information allows for an estimation and comparison of specific dietary patterns, also highlighting the worldwide most critical nutrients in current diets. Instead, our analysis focuses on the different dietary protein options and answers the common question of whether substituting animal foods (meat, eggs, and dairy) with legumes, the primary source of plant protein, could lead to an average decrease in water demand of a meal or diet. On a global level, only targeting caloric substitution would lead to a decrease in average water demand if legumes replaced animal foods. However, in this case the total amount of protein would decline while carbohydrate supply would increase. This means that, if macronutrient shares in a given meal or diet were to be held stable, with legumes supplying an equal amount of protein as animal foods, legumes would not only lead to a substitution of animal products in a diet but also of certain amounts of other carbohydrate sources. Figure 3 compares the micronutrient content, calories, and water demand that are associated with1 g of protein from either legumes, soybeans, dairy, eggs, or meat with and without the inclusion of offal. The black bars indicate the total range of average water uses for different

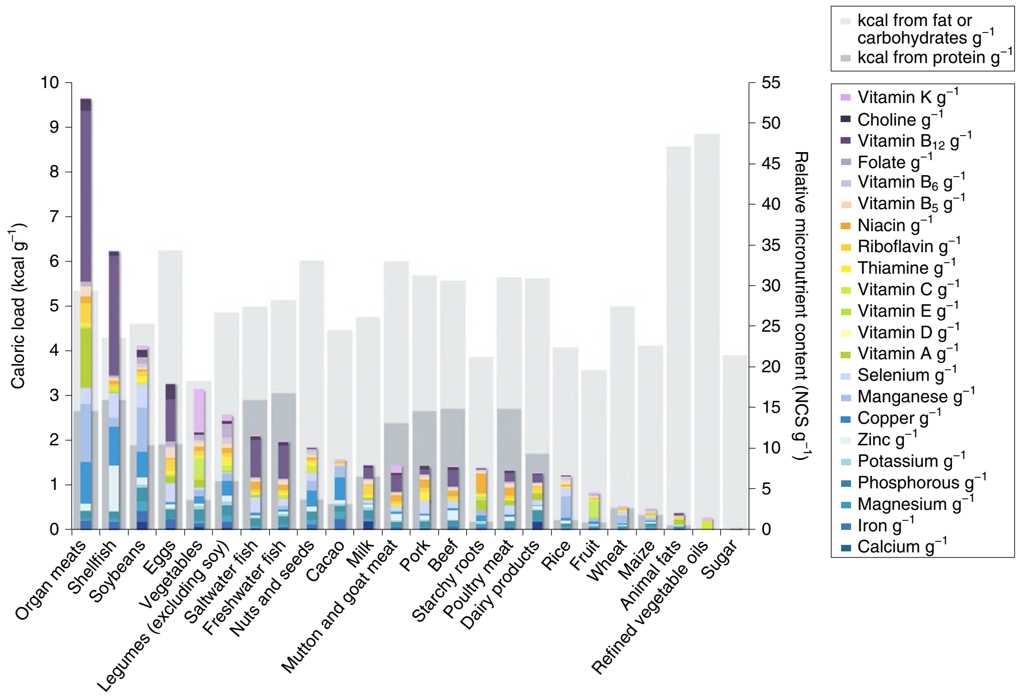

Fig. 1 | NCS for 24 food groups. NCS are based on food weight and displayed per gram net weight. Foods are ranked according to their overall score on the right *y* axis from highest (left) to lowest (right). The stacked bars show specific nutrient content shares as a percentage of the respective RDA, which when added up, amount to each food's specific NCS. Certain animal foods, legumes, vegetables, nuts and seeds show the highest nutrient concentrations of 22 essential minerals and vitamins; sugar and fats rank lowest. The underlying light grey bars relate the NCS to its respective overall caloric load and protein content per gram of food (left *y* axis), with animal products showing the highest protein shares within the overall caloric load. Exact values and scores based on caloric content instead of food weight can be found in Supplementary Table 1 and Supplementary Fig. 1.

legume and meat options. Soybeans are depicted separately because large regular intakes are not documented for current or historic human diets and might not be regarded safe from a health perspective (see Discussion). On average, legumes show lower total water demand per gram of protein than animal protein sources, −7, −19, and −34%, compared to dairy, eggs, and meat, respectively. Beef and beans show the highest water demand while poultry and peas rank lowest. Hence, the specific type of protein source matters since animal foods such as chicken show higher water-use efficiency with regard to protein than, for example, beans, lentils, and groundnuts. Looking at the supply of various micronutrients, overall legumes appear superior to meat, eggs, and dairy, although bioavailability of various minerals is lower than in animal products. Combined with a lack of (preformed) vitamin A and B_{12}, this makes a direct comparison on the basis of micronutrient content problematic.

Since global values provide only a very general idea of the water footprints of different foods, we further investigated more regionalized water footprints of protein sources. Figure 4 depicts the total water demand of each major protein source for each continent. Water data were taken from the respective largest national producer from each world region[2]. The first set of columns shows the world averages as presented in Fig. 3. There is a considerable variability in water use and shares of green and blue water demand for dietary protein sources. The average water demand for legumes appears lower than for most animal foods in most regions, with the biggest exception being Australia/Oceania. While these regional data largely support our general global findings, the variability within legume and meat sources can differ regionally. For example, beef shows the highest water use per gram of protein in all parts of the world; however, in North America, goat meat ranks slightly higher. Also, groundnuts generally show comparably low water demands, although being the most water-intensive plant protein source in Africa.

In conclusion, the water needs of many protein sources (peas, groundnuts, lentils, dairy, eggs, chicken, and pork) globally fall within a range of 13.3–23.3 l g^{-1} protein. A potential variability of these values of just ± 10% could easily change the particular ranking of specific protein sources within this range (see Supplementary Table 3b). Soybeans show on average the lowest water demand for legumes with 11 l g^{-1} protein. Regarding animal protein, ruminant meat (and dairy) stands out for two reasons. First, ruminant meat deviates significantly from these average values with a much higher water demand across all regions, hence skewing the average water use for meat. In regions such as North America or Europe, where cereals or soybeans are grown (or imported) and fed to livestock, ruminants are partially competing for water resources with plant foods. We estimated that if the amount of water required to produce cereals and soy as feed was instead used to grow legumes, the edible protein output for humans would be approximately 3.5 times higher. In other world regions such as Africa or South Asia, where in many parts water resources are scarce, the high water demand for ruminant meat and dairy stems predominantly from water used for producing grass and crop residues as feed[30]. Despite a comparatively high water demand, these water resources cannot be used directly for plant food production and hence do not stand in direct competition with crop production. It is currently estimated that 86% of livestock feed is not edible for humans, and 77% of pasture used for livestock could not be converted into cropland[31]. Therefore, direct competition for both green and blue water resources between animal and plant foods only occurs regionally, for example, in Southern Europe, where limited water resources are used to produce cereals as livestock feed.

Discussion

When evaluating the sustainability of food production, more comprehensive environmental and nutritional approaches are required.

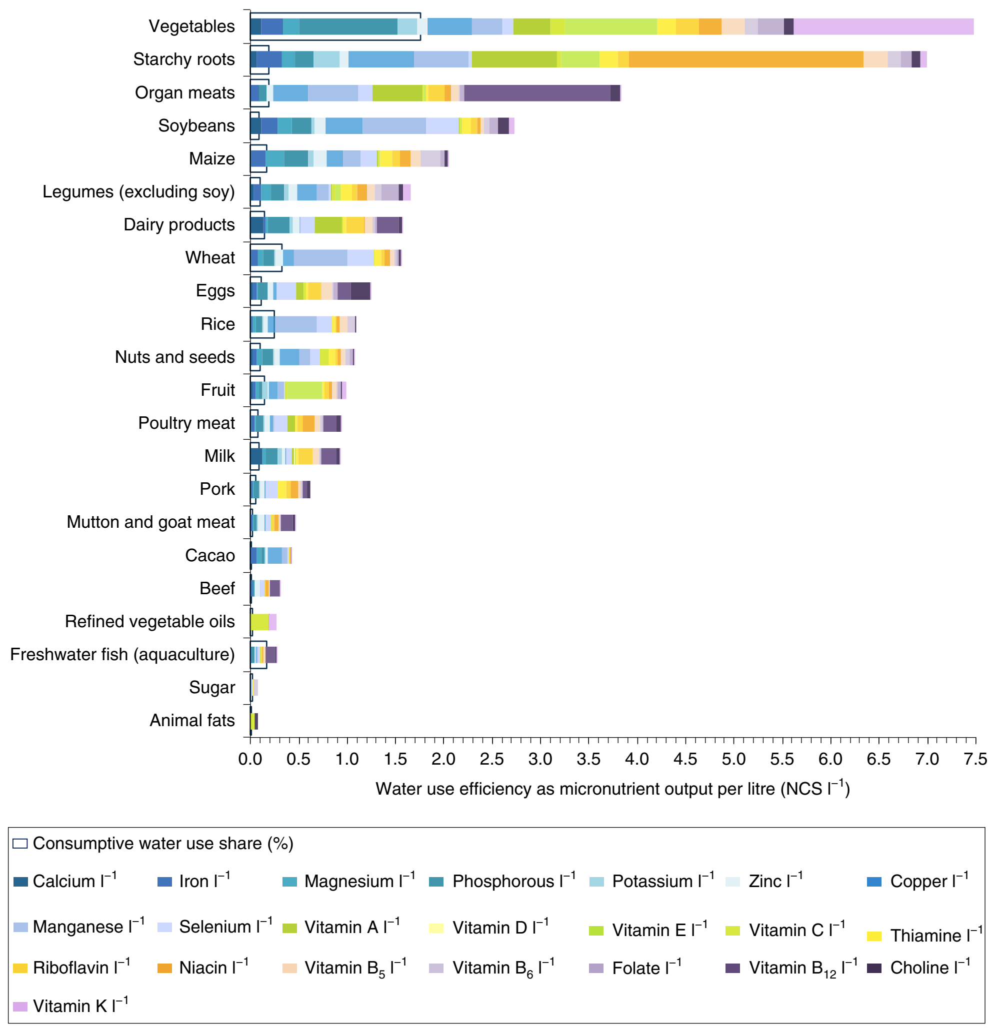

Fig. 2 | Global average water-use efficiency per litre net water use. The stacked bars show the added amounts of 22 essential micronutrients as a percentage of the respective RDA (NCS) per litre overall net water use (green and blue water). The underlying dark outlined bars depict the relative amount of water required for irrigation and processing (blue water) as a percentage of the total water use of 1 l for each food group. Vegetables and starchy roots show the highest overall water-use efficiencies with regard to dietary nutrient production, with vegetables showing a relatively high share of blue water demand. Combining organ and muscle meat, meat would place ninth in the overall ranking, with a 6% blue water share. Wild-caught fish and seafood are not depicted in this graph. The exact values including blue water shares can be found in Supplementary Table 2; Supplementary Fig. 2 depicts the water use efficiencies solely per litre of water consumed (blue).

Besides land and energy use, water is just one major determinant for agricultural sustainability. The prioritization of specific environmental pressures over others depends on the regional environment and urgency of the negative impacts. In water-rich regions, GHG emissions might be of higher importance than in regions where water resources are scarce. A diet providing a wide variety of nutrient-rich foods in quantities that are compatible with an individual's needs and preferences according to age, sex, lifestyle, and health status would not only contribute to a balanced and nutritious diet, but also shows on average high comparative water-use efficiencies, including consumptive water use. When the goal is to reduce the water footprint of entire dietary patterns, there are several possibilities. One option would be to reduce food waste[32] or the total amount of food consumed. However, in most world regions food intake is estimated to be either adequate or too low. Another option would be to shift away from ruminant meat towards higher shares of chicken, pork, legumes, eggs, and dairy (or fish if caught wild or from sustainable coastal aquaculture). In regions such as North America and Europe, where regional water resources are abundant, this would free further water resources but would lead to a decline in the supply of some critical micronutrients such as iron, zinc, and vitamin B_6 and B_{12} in the current diet. However, in other world regions such as sub-Saharan Africa or South Asia, the current per capita intake of dairy and ruminant meat is very low and water resources for livestock for the most part do not compete directly with resources for plant foods. Hence, in these specific regions, other substitution options would result in a more efficient water use, for example, replacing rice and sugar with more nutritious vegetables, fruit, and starchy tubers, while simultaneously also reducing GHG emissions that are stemming from rice. A third option would be to reduce total protein supply. The currently recommended energy intake from protein is set at 10–35% of the total caloric intake. Today's reported consumption ranges between approximately 10% in low-income countries and 15% in high-income countries, and thus already falls at the lower end of this range.

Regarding other macronutrients, fat, and carbohydrates, replacing cereals, sugar, and certain fats with more nutritious food sources, for example, vegetables, nuts and seeds, legumes, fruit, or olive oil could lead to an increase in water demand. Increasing the diversity of meat consumption by including offal would increase the nutritional value

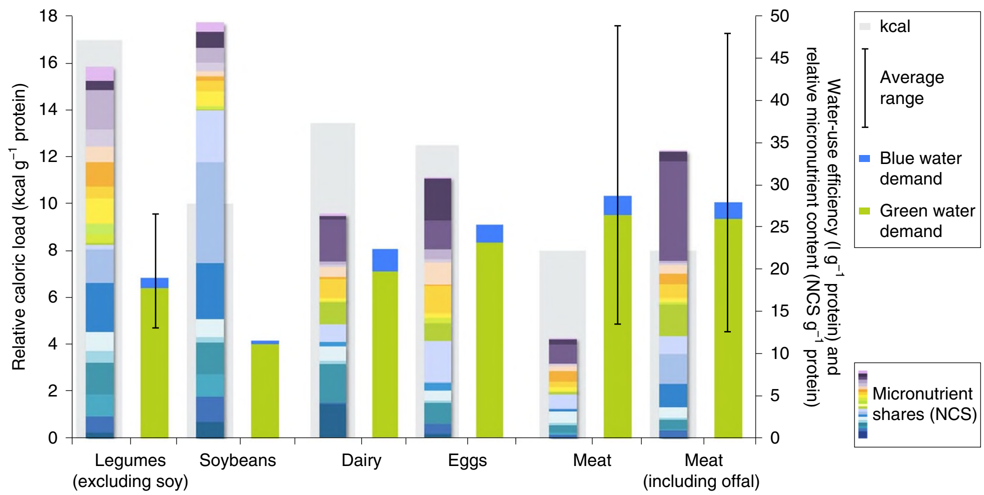

Fig. 3 | Micronutrient content and water demand per gram of protein. Total water demand (l) is displayed in the form of stacked columns, presenting green and blue water shares. The most water-efficient protein sources, with the exception of soybeans, are peas and chicken. The black bars for legumes, meat, and meat including offal indicate the total water-use ranges for different food types (average values for peas, groundnuts, lentils and beans, and chicken, pork, goat and mutton, and beef). The stacked multicoloured columns show the associated micronutrient content. The highest NCS associated with a food's protein content can be found in legumes, although bioavailability of some minerals might be limited. The micronutrient content of meat appears low when edible offal is not included. The light-shaded bars in the background display the respective caloric content for each protein source. The exact values can be found in Supplementary Table 3a,b.

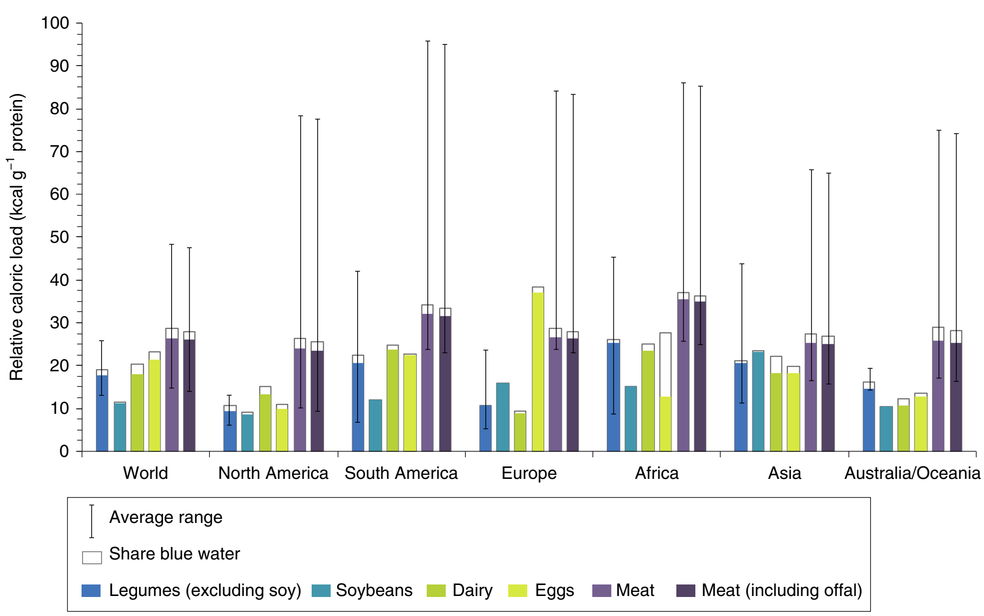

Fig. 4 | Comparing global water demands for major dietary protein sources. The first set of columns depicts the global averages presented in Fig. 3. The data for each continent were taken from the respective largest producer of each protein source in each region (legumes: United States/Canada, Ecuador/Argentina/Brazil, Belarus/Russia/Greece, Ethiopia/Tanzania/Congo/Sudan, India/Myanmar/China, Australia; soy: United States, Brazil, Ukraine, South Africa, India, Australia; dairy: United States, Brazil, Germany, Kenya, India, New Zealand; eggs: United States, Brazil, Russia, Egypt, China, Australia; meat: United States/Mexico, Brazil/Argentina, Russia/Greece/UK/Germany, South Africa/Algeria/Nigeria, China, Australia). The black bars for legumes, meat, and meat including offal indicate the total water use ranges for different food types (average values for peas, groundnuts, lentils and beans, and chicken, pork, goat and mutton, and beef). Regional patterns largely follow the global pattern. On average, most legumes, dairy, eggs, chicken, and pork show relatively similar water use efficiencies with regard to protein. Regional water demands for soybeans fall within the range for legumes in all regions except for Australia/Oceania. Ruminant meat shows the highest total water demand across all regions. The exact values can be found in Supplementary Table 4.

of average diets, while also improving water-use efficiency when evaluating the resource impact of meat consumption. This could be of importance for the nutritional status of the population in both high- and low-income countries. A complete replacement of cereals with starchy roots in the diet would lower agricultural water demand by 25%. Besides improving water management in different agricultural systems, exploring alternative, currently less accepted/available food choices both from animal and plants sources, could potentially offer better options to improve the quality of diet worldwide while limiting/reducing the water footprint of agriculture.

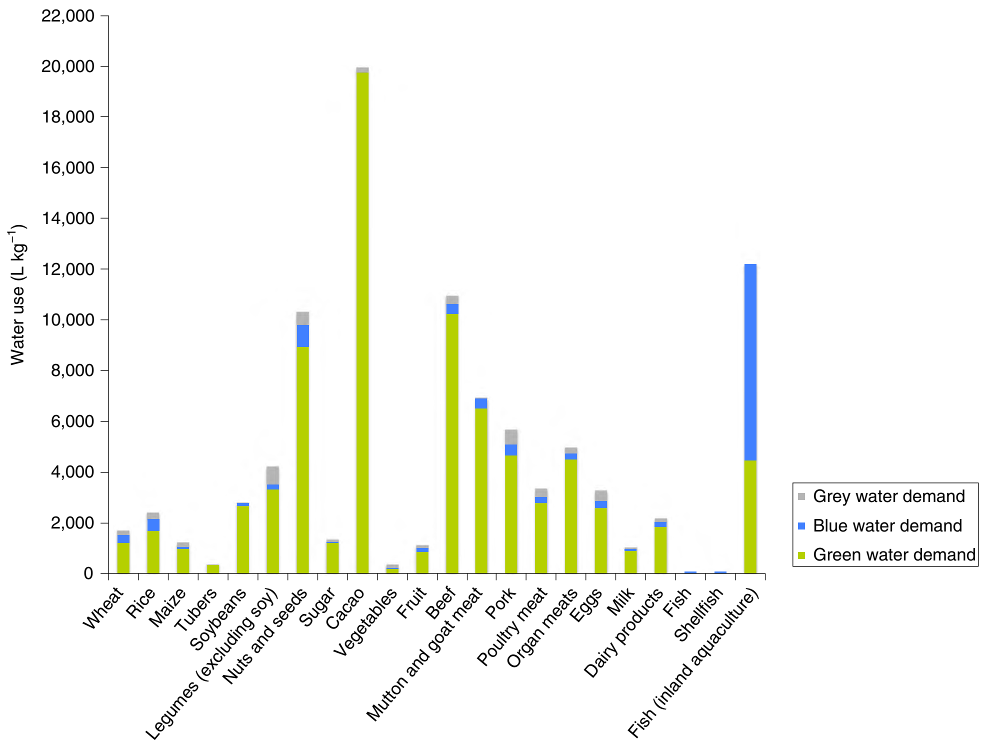

Fig. 5 | Water footprint of 24 main food groups. The stacked columns depict the global averages of green, blue and grey water demands in litres per kg. The data on fish from inland aquaculture were adapted from Verdegem et al.[46].

Previous research concluded that diets providing smaller amounts or no animal protein could lead to a reduction of the average total water footprint of diets[33,34]. The differences in water demand between most animal and plant protein sources appear small; given the uncertainty within global modelling approaches, which include meteorological input data, assumptions on growing cycles, and crop water requirements, we do not find large saving potentials when substituting animal with plant protein foods. The only foods that stand out in terms of their relative water demand per gram of protein are soybeans—with the lowest global average water use (in particular in regions such as South America and Africa)—and ruminant meat with the highest water demand across all world regions. However, water resources for ruminants only compete with water for plant foods when crops are included as feed in animal diets. Since previous studies are based on the same data set and similar methodological approaches, our findings suggest that a distinction between different plant and animal protein sources appears to be necessary to obtain more realistic food options for potential future diets. In contrast to other studies, we treated soy separately from other legume types because a substantial soybean intake might increase mineral needs due to low bioavailability, increase iodine demand, and lead to potential endocrine disruption resulting from high isoflavone contents[35–39]. The Taiwanese population currently shows the highest reported and considerably safe soy intake, averaging approximately one serving of soy products (approximately 10 g of protein) per capita a day[40].

Our analysis is a comprehensive investigation regarding global water use efficiencies of food production with respect to nutritional outputs. Both plant and animal foods can provide various, although yet not completely interchangeable, sets of nutrients that can complement each other as parts of a balanced diet. While certain plant foods such as vegetables, legumes, nuts, seeds, and starchy roots show the highest nutrient content per gram net weight as well as often the highest water-use efficiencies, animal products are used most efficiently when all edible parts of the animal make part of a diet. Regarding both the health and environmental challenges that current and future generations are facing, a stronger focus on the nutrient density of diets could improve the average nutritional status of the population, while also increasing water-use efficiency in agriculture. However, total water requirements for food production might increase depending on the specific substitutions of foods that could be envisioned for future diets.

Methods

Global water-use data. To estimate the average global water demand for a wide range of food products, the Water Footprint Network (WFN) database offers information in the form of green, blue, and grey water demand on a country and catchment basis[41,42]. Green water is defined as rainwater that stays on the surface, including vegetation. Blue water is defined as consumptive water demand, that is, water that is not directly returned to its source. Grey water accounts for a hypothetical amount of water that is required to dilute pollution stemming from commodity production. Hence, it can be used as an indicator for potential water pollution. If multiple goods can be produced from the same source, for example, a cow offers milk, meat, leather, and so on, total water demand is allocated according to the individual product's economic value on the global market. Both, the hydrological modelling for the 1996–2005 period on which the WFN product data are based, as well as the products' associated economic value, limit the use for future projections of water use since both variables might change over time. Focusing on average water use for food production, we used the global average data as listed in the WFN database. This data set offers data on food groups, including animal products, most comprehensively. Global averages were calculated using the weighted average production of each crop for each country. Food group categorization in the WFN database matches that in the FAO's global database[2], although in some cases, for example, dairy, averages from the WFN data had to be calculated to match food groups as they are defined by the FAO. By using global averages, we also included any water demand associated with the international crop trade. This accounts for about 13% of total water requirements[43]. Wood et al.[3] present a more in-depth analysis on the international nutrient trade. Also, the sustainability of blue water use is not reflected in the WFN data. In some regions, irrigation water needs are met through an unsustainable use of groundwater resources[44]. However, water use efficiencies for livestock include virtual water data for feed imported from other world regions. Therefore, changing feeding patterns and feed water-use efficiencies in the future might impact water demand for animal products. Water-use efficiencies in agriculture vary from region to region, although all world regions include (projected increasing) areas of physical and/or economic water scarcity[1,45]. Climate change will lead to a change in rainfall patterns in many parts of the world, increasing or decreasing the need for irrigation water and hence influence the consumptive water use efficiencies of foods.

Figure 5 shows the water demand for 24 main food groups. We applied non-weighted average water use was for most food groups with the exception of vegetables and fruit, where weighted averages were calculated according to specific food shares as reported in the annual Food Balance Sheets by the FAO. In this study, particular focus was placed on consumptive (blue) water demand as well as overall water demand by adding rain (green) water use to blue water demands. For animal foods, 90%+ of water demand stems from water requirements for feed production. Feed crops, such as cereals and soy, are mostly used for poultry and pigs, whereas ruminants predominantly rely on grass and crop residues. As water pollution is not adequately addressed in all world regions, the potential grey water demand associated with food production remains hypothetical at this point and was not included in our analysis. The WFN database does not provide water demand for fish production. While water use in natural aquatic environments is negligible, aquaculture requires large amounts of water, partly due to evapotranspiration when fish is kept in freshwater ponds, and partly due to the water demand associated with feed production. Verdegem et al.[46] estimated the water use for animal production through aquaculture by including blue and green water use for feed production from the IMPACT database. To integrate those estimates in our analysis, data were converted to WFN values and total average water use for inland aquaculture was added to the analysis.

Nutrition data. Data on the nutritional values of foods were taken from the United States Department of Agriculture (USDA) National Nutrient Database for Standard Reference[47] since this database is the most comprehensive source of food composition data to date, including prepared food items. Local and regional differences in nutrient contents occur but are specific to each micronutrient. When comparing with other food composition tables (for example, the Indian Food Composition Tables[48]), we find that total nutrient contents in the form of NCS show only relatively small deviations, while specific nutrients can deviate much more strongly, changing the shares of nutrients within the NCS. No general regional deviation patterns in specific foods or food groups could be detected. To match that information with data on global food supply and its associated water use, only whole foods, that is, foods that are either unprocessed and unrefined or processed as little as possible and refined, were included. For example, milk products such as cheese or cooked/roasted plant foods were included; wheat was mainly included in the form of whole or refined flour. All foods lose nutrients to varying degrees when being prepared for human consumption. We only used data on the nutrient content of edible food products within each group, that is: animal products other than pasteurized dairy are cooked; cereals, starchy roots, and legumes are cooked or baked; fruit and vegetables are averaged for raw and cooked products; and nuts and seeds are also averaged for raw and roasted products. To link a food's nutritional profile to its specific water use, many food items had to be corrected by adjusting for changing water weights from a raw to a cooked state. If such data were not available, for example, the nutrient values of baked cereal flours, nutrient retention factors were applied[49]. This conversion makes it possible to relate the nutrient content of various food groups as they are consumed by humans to their recommended intake levels, before linking them to the specific water demand of food production. Existing nutrient scoring methods for foods and diets often include various numbers of essential minerals and vitamins, while simultaneously also discounting for certain nutrients believed not to be beneficial to human health, and comparing different foods either on the basis of weight or kcal[50,51]. We chose not to adopt any of the existing scoring methods for three main reasons. First, because of the exclusion of essential micronutrients, which are often supplied insufficiently in current diets, such as vitamin C or B_{12}(refs. [52,53]). Second, because whole foods with a high natural fat content are given less weight in the comparison due to their high caloric content. And third, because of certain contradictions within the scoring methodology. Fibre, for example, can be found in the group of recommended nutrients. This includes soluble fibre, which is metabolized to butyric acid in the gut, supporting a healthy microbiome[54], while all saturated fats directly supplied by foods, including those that are potentially beneficial such as butyric, lauric, and trans-palmitoleic acid are not recommended according to these scoring methods[55]. All three factors skew nutrient scores in favour of plant foods.

In our analysis, we included 22 essential micronutrients: calcium; iron; magnesium; potassium; phosphorus; manganese; zinc; copper; selenium; vitamin A, C, D, E; thiamine; riboflavin; niacin; pantothenic acid; vitamin B_6; folate; vitamin B_{12}; vitamin K, and choline. Data on iodine and fluoride content were not available. Vitamin A values refer to retinol activity equivalents, vitamin D values combine vitamin D_2 and D_3, vitamin E refers to α-tocopherol, and vitamin K does not distinguish vitamins K_1 and K_2. We did not discount for any naturally occurring micronutrients or macronutrients. We excluded fortified foods, or any other highly processed foods containing added sugar, sodium, fibre, or industrial flavours, which could influence nutritional values and palatability. Sample sizes for different food groups varied largely; hence, the average values for specific nutrient concentrations were calculated. Median values were used only for large variations in small sample groups. Data on the nutrient content of foods are given in various units per 100 g of food product in the USDA database. To integrate all nutrient data in one scoring method, mineral and vitamin contents were converted from their standard unit of measurement (mg, μg, international units) to the percentage of their RDA. RDAs give the amount of nutrients estimated to be sufficient to meet the requirements of healthy adults. Estimates are set above the absolute minimum requirements but are not necessarily considered optimal values for achieving long-term health[56]. In the form of an NCS, these data are summed up and compared on a net weight basis. Thus, the NCS neither have a theoretical upper limit, nor do they adjust for a specific nutrient profile by weighing each nutrient to account for a balanced supply of minerals and vitamins. Since we did not compare entire diets, where a balanced intake of nutrients should be the goal, but rather individual foods, the specific nutrient profiles of foods can complement each other in a diverse diet. Net weight refers to the nutritious part of the food, hence deducting the water content of a 100-g serving of food either cooked or uncooked if edible in that state. This step insures that foods such as vegetables do not get penalized due to their high water content. Overall, fibre content is still included in the net weight. Our score does not combine the nutrient and calorific loads of food servings because this would discount nutrient-rich foods, which simultaneously show a high caloric load.

$$\mathrm{NCS} = \frac{\sum_{n=22} \text{amount of nutrient } x \text{ per 100 g of food } y/(\mathrm{RDA}_x/100)}{\text{Net weight of } y\,[100\text{ g}-\text{water weight}]}$$

The water-use efficiencies of foods are then calculated by dividing the NCS of a specific food by its associated water demand:

$$\text{Water} - \text{use efficiency} = \frac{\text{NCS of food } y}{\text{Water demand (l) per gram net weight of } y}$$

Data limitations. There are several limitations to our analysis that might have led to over- or underestimation of the nutritional value of certain food groups: (1) main cereals (wheat, maize, rice) were primarily included in the form of refined grains (90%+; for whole grain data, see Supplementary Fig. 3a); (2) the accuracy of the RDAs and bioavailability of nutrients also must be taken into account when evaluating the nutritional value of foods. Assessment methods for recommended intakes vary among different micronutrients. The resulting uncertainties might influence the estimated nutritional value of specific foods. For example, recent studies on adequate vitamin B_{12} intakes estimate almost 70% higher intakes than currently recommended[57]. This would lower the vitamin B_{12}-specific water use efficiency accordingly, but only have a small effect on total water-use efficiencies. Food group rankings according to water-use efficiencies would almost remain identical, with only wheat and beef, as well as poultry and fruit, respectively, switching their placing. However, this finding also increases the overall value of animal foods in a balanced diet. With the exception of iron and zinc, bioavailability of nutrients is not directly considered in the RDAs. We used the respective RDAs for a high dietary bioavailability of these minerals. A low consumption of animal foods would increase the recommended intakes for certain nutrients and hence lower the relative nutritional value for plant foods such as legumes[58–60]; (3), regarding animal products, several other nutrients (iodine, vitamin K_2, eicosapentaenoic acid, and docosahexaenoic acid) can be found predominantly in fish, meats, offal, and tissues; these were not included in this analysis due to limited data availability. Only being able to consider these last two points on a qualitative level at this time, we would expect legumes to rank somewhat lower and some animal foods somewhat higher in our nutritional ranking of food groups, although our general findings would probably only change to a small degree.

With regard to the application of water-use data, two factors might influence the validity of our results: (1) the application of WFN data for animal foods is based on the assumption that both the shares of products coming from the same animals, for example, the number of eggs per hen, and their economic value remain stable. A change of these variables would thus affect the relative amount of water allocated to a specific animal product; and (2) wild-caught fish shows by far the highest water use efficiencies, since the evaporation rates of natural water bodies were not allocated to the water requirements of fish breeding. However, a sustainable supply is limited by natural capacities. Instead, depending on the specific environment, fish from aquaculture might lead to high water demands. We included the average data from inland aquaculture fish fed with standard (grain) feed, living in freshwater ponds that show average evaporation rates. Different feed types, such as high protein feeds, can reduce overall water demand[46]. Fish grown in brackish or saltwater bodies show a much lower water demand when evaporation rates are not attributed to water demand.

Data availability

The data generated from this analysis are included in this published article and its Supplementary information. Additional data from the Supplementary Information are available from the corresponding author upon reasonable request.

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Author contributions
K.D. and M.H. conceived the project. K.D. developed the analysis approach. K.W., M.H. and K.D. contributed to the study outline. K.D. wrote the paper.

Competing interests
The authors declare no competing interests.

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