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Opportunity for a Dietary Win-Win-Win in Nutrition, Environment, and Animal Welfare

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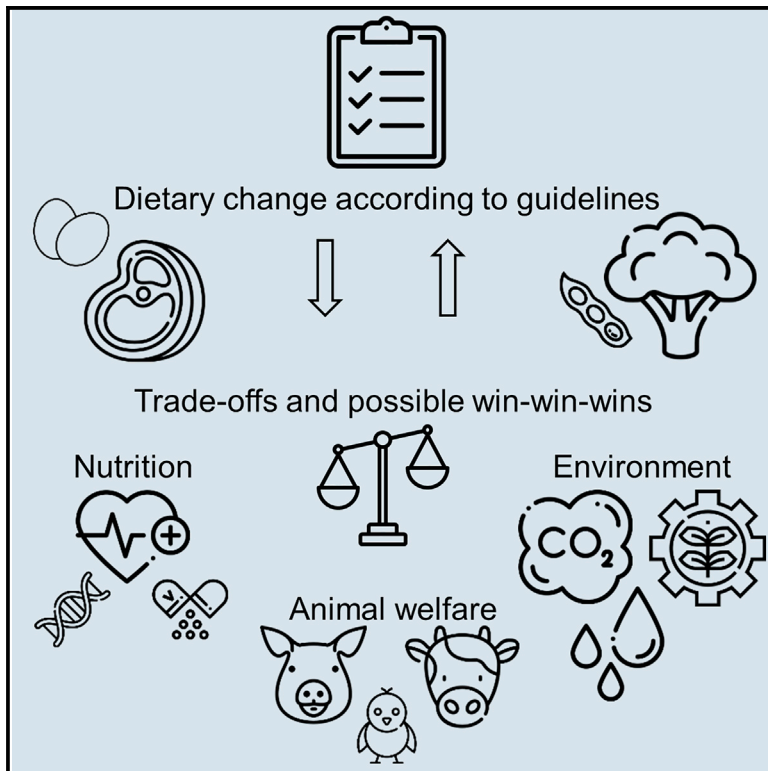
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One Earth

Opportunity for a Dietary Win-Win-Win in Nutrition, Environment, and Animal Welfare

Graphical Abstract



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In Brief

Food systems are a key determinant of human health, environmental sustainability, and animal welfare. Consequently, dietary changes have the potential to raise sustainability across multiple dimensions. Scherer et al. assess the impacts of following nation-specific dietary recommendations for 37 countries. They show that win-win-wins are possible, but their potential is rarely exploited. Instead, many countries face trade-offs. Such trade-offs also depend on the specific animal products that are decreased or increased.

Highlights

- Using a recently developed framework, we assessed animal welfare at a large scale
- Many countries face trade-offs between nutrition, environment, and animal welfare
- Win-win-wins are possible for dietary changes but rarely realized
- There is a need to carefully revise dietary guidelines



Opportunity for a Dietary Win-Win-Win in Nutrition, Environment, and Animal Welfare

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SCIENCE FOR SOCIETY The negative impacts our food consumption habits have on both the environment and animal welfare, in addition to our personal health, is being increasingly exposed, with strong calls to reduce our consumption of meat and other animal products. Despite these escalating concerns, the consumption of animal products continues to rise. Here, we assess the trade-offs between nutritional quality, environmental sustainability, and animal welfare when following the nationally recommended diets of 37 countries and where win-win-wins are possible. We find that although most countries would indeed reduce their consumption of animal products were the average diet to follow national guidelines, many face trade-offs between associated impacts. There remains scope to improve and optimize national dietary guidelines in many countries.

SUMMARY

Sustainable food systems are essential for meeting nutritional requirements, limiting environmental impacts, and reducing animal welfare loss. Although current dietary trends in many regions rather go in the opposite direction, the adequacy of dietary guidelines is unknown, and the three sustainability dimensions are generally not assessed simultaneously. Here, we assessed nation-specific recommended diets for these impacts compared with the average diet. We assessed the trade-offs between nutritional quality, environmental sustainability (carbon, land, and water footprints), and animal welfare. Most countries reduce their animal product consumption in terms of food calories when switching to the nationally recommended diet. Recommended diets have the potential for “win-win-wins” in all three categories when compared with the current average diet, such as that shown in Brazil. However, South Korea loses in all three regards, and many other countries face trade-offs. This highlights the scope for the optimization of dietary guidelines to minimize such trade-offs.

INTRODUCTION

Food production, and the demand it supplies, has large impacts on many different areas of the natural world, and interacts with all

Sustainable Development Goals.¹ Agriculture has also been identified as a major driver for transgressing or risking transgressing several planetary boundaries.² Three main impacts are those on human nutrition, the environment, and animal welfare. The moral boundaries of humans, i.e., the entities deemed worthy of moral consideration, greatly differ among individuals, but have generally expanded over the last few centuries.^{3,4} Increasing numbers of people are concerned about the impact human diets have on the environment and the welfare of animals. Several studies have suggested that production systems can only improve so much and are generally insufficient to achieve sustainability. Ultimately, the transition to sustainable food systems will require a simultaneous transition on both the production and demand sides.^{5–9} On the demand side, dietary changes play a key role. Diets link human health, environmental sustainability,^{1,10} and animal welfare.¹¹ Therefore, dietary changes may offer an opportunity for a triple win.

The link between the environment and food consumption has been made in several studies. Tilman and Clark¹⁰ found that alternative diets (Mediterranean, pescatarian, and vegetarian), characterized by lower meat consumption and higher consumption of vegetables and fruits, offer both health and environmental benefits. Tukker et al.¹² showed that healthier European diets with less meat reduce environmental impacts without significant rebound effects from changed food expenses. Reynolds et al.¹³ reviewed the environmental impacts of dietary recommendations by the World Health Organization (WHO), which promote healthy eating and also imply lower meat consumption along with higher consumption of vegetables and fruits. They confirmed that healthy diets have the potential to reduce environmental impacts. Similarly, Springmann et al.⁹ analyzed the



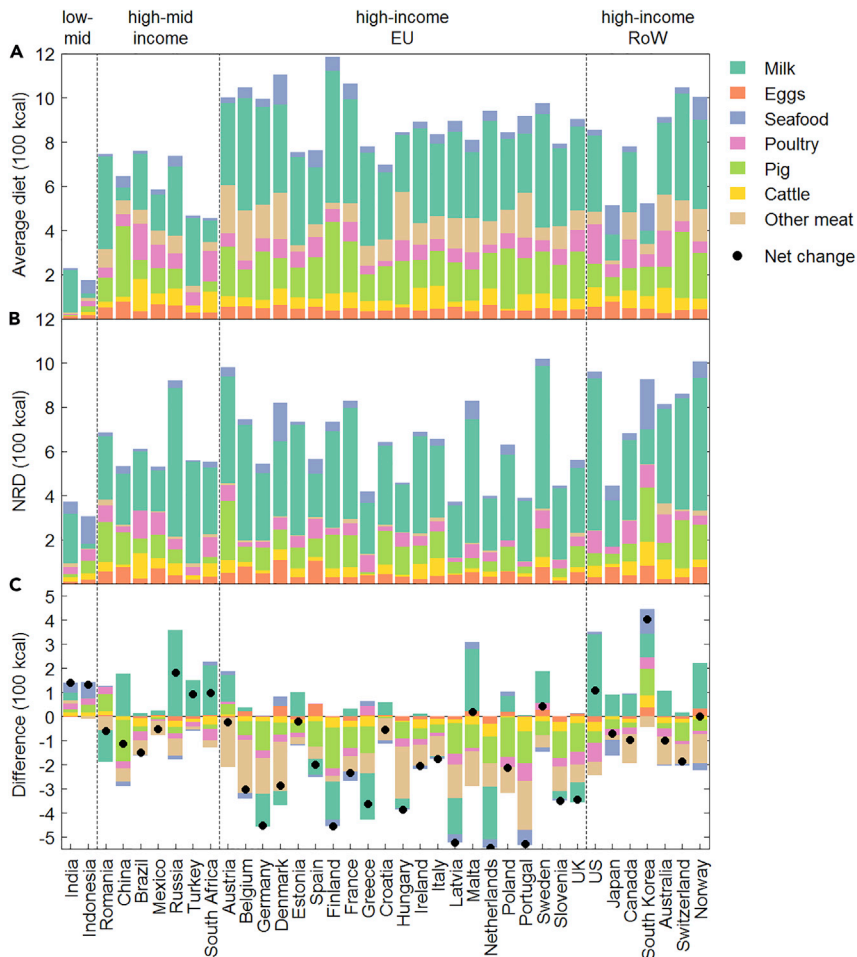


Figure 1. Composition of Food Energy Intake by Animal Product Category per Person per Day

Energy intakes are measured in kilocalories (kcal), and shown for (A) current average diets, (B) nationally recommended diets (NRD), and (C) the difference between them. Note that nationally recommended diets were scaled so that total calorie intake matches that of the current average diet (isocaloric approach). See also [Figure S1](#) for food intake in terms of mass. The raw data associated with this figure are available in [Data S1](#).

et al.¹¹ were among the first to quantify impacts of animal product consumption on animal welfare. Interestingly, improvements in animal welfare include not only a reduced consumption of animal products but also a shift toward less harmful animal products.

In this study, we investigate the possibility of a win-win-win outcome of switching to a nation-specific recommended diet in animal welfare, nutritional, and environmental impacts. Because resolving debates about animal welfare cannot solely rely on science, and we must recognize that the diverse value judgments among people may result in different conclusions for the same empirical findings,²¹ we offer multiple indicators to accommodate this value pluralism. The three indicators are expressed in (1) animal life years suffered (ALYS), (2) loss of animal lives (AL), and

(3) loss of morally adjusted animal lives (MAL). We further consider nutritional impacts using a modified nutrient-rich foods (NRF) index²² and environmental impacts using the carbon footprint, land footprint, and water scarcity footprint (in the following called water footprint). The [Experimental Procedures](#) section provides further information on these indicators.

impacts of following WHO guidelines or a more healthy and plant-based, flexitarian diet. They found that dietary changes are especially effective in reducing greenhouse gas emissions. Shepon et al.¹⁴ optimized diets to minimize cropland use, and found that replacing animal products with plant-based alternatives, such as soy, far exceeds the benefits of eliminating all food losses. Behrens et al.¹⁵ found that, across 37 nations, the adoption of nation-specific recommended diets generally reduces environmental impacts. This especially applies to high-income nations, whereas impacts might increase by a small amount in lower middle-income nations. The impacts are mainly driven by the consumption of animal products.

Work on assessing the animal welfare of diets and foods is at an early stage. Its importance is underlined by research showing that an increasing number of animals are sentient and able to suffer.^{16–18} Gustafson et al.¹⁹ defined seven food system metrics to assess sustainable nutrition security, and their metric on socio-cultural wellbeing includes the animal protection index²⁰ as an indicator for animal health and welfare. However, the animal protection index gives qualitative scores related to countries' commitments to protect animals, and covers, besides production animals, also wild animals, lab animals, zoo animals, and companion animals. Therefore, the animal protection index is not suitable to assess the impacts of dietary changes. Scherer

(3) loss of morally adjusted animal lives (MAL). We further consider nutritional impacts using a modified nutrient-rich foods (NRF) index²² and environmental impacts using the carbon footprint, land footprint, and water scarcity footprint (in the following called water footprint). The [Experimental Procedures](#) section provides further information on these indicators.

RESULTS

Dietary Changes

Most countries (27 out of 37) reduce their animal product consumption (by calorie) when switching from the current average diet to the nationally recommended diet ([Figures 1](#) and [S1](#)). Exceptions are Norway, Malta, Sweden, Turkey, South Africa, the United States, Indonesia, India, Russia, and South Korea. Except for Norway, Malta, Sweden, and the United States, the current average diet in these countries includes animal product consumption below the average of the analyzed 37 countries. This is especially true for Indonesians and Indians who currently consume relatively few animal products. Norway's, Malta's, Sweden's, and the United States' high animal product consumption is already dominated by milk in average diets (40%, 37%, 53%, and 40%), and its share increases further under the nationally recommended diet (59%, 67%, 63%, and 71%). Following

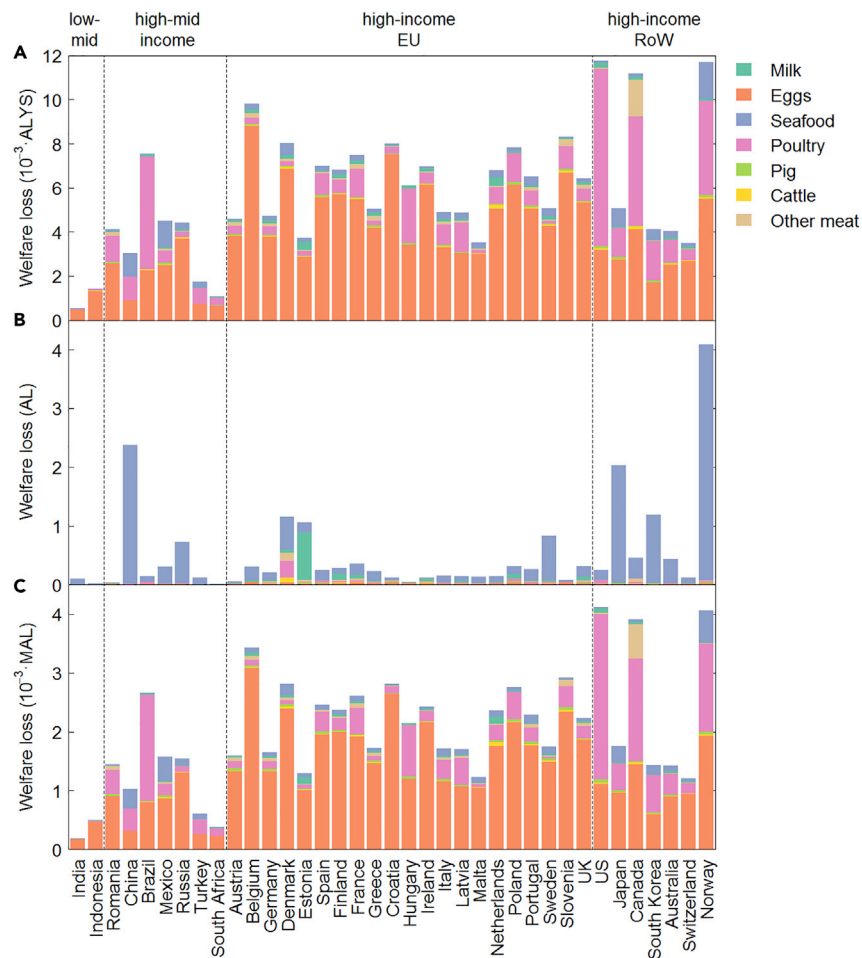


Figure 2. Absolute Animal Welfare Loss of Current Average Diets per Person per Day

Animal welfare loss is expressed in (A) animal life years suffered (ALYS), (B) loss of animal lives (AL), and (C) loss of morally adjusted animal lives (MAL). See also [Figure S2](#) for environmental impacts. The raw data associated with this figure are available in [Data S1](#).

important. Seafood impacts an even larger number of animals, as revealed in the animal welfare loss expressed in AL, but their welfare loss ranks much lower in terms of ALYS because their life quality is only compromised to a small degree (not at all if wild-caught), and the slaughter duration is relatively short. Also, for seafood, animal welfare loss is discounted for MAL due to their low moral value (which approximates their sentience and self-awareness). As an exception, milk drives a large share of the animal welfare loss in AL in Estonia. However, Estonian milk consumption mostly affects fish or other aquatic animals used to feed dairy cows. This reflects the fact that many animals are used as feed for other animals in food systems—poultry and aquatic animals (e.g., poultry meal and fish meal) are widely used as protein sources for livestock.

In this analysis, seafood also includes bivalves, which cause animal welfare loss of the same order of magnitude as eggs.

This is because, although they have an

guidelines results in meat consumption decreasing most often (33 out of 37 countries), while milk and derivatives is the only animal product category in which most guidelines (25 out of 37 countries) suggest an increase. India, Russia, and South Korea increase their animal product consumption the most. Because the current consumption in India is very low (rank 2 out of 37), it remains comparably low according to the national diet recommendation (rank 3). However, by moving from average to recommended diets, Russia's and South Korea's consumptions exceed the average of the 37 countries. Guidelines in Latvia, Portugal, and the Netherlands envisage the most drastic reduction in animal product consumption, by more than 50%.

Animal Welfare Associated with Average Diets

Animal welfare loss associated with the current average diet is mostly driven by poultry and egg consumption (for ALYS and MAL) and by seafood consumption (for AL) ([Figure 2](#)). Poultry and eggs (through laying hens and male chicks) cause disproportionately high animal welfare loss because of the larger number of affected animals compared with other meat or milk. The number of affected animals depends on the product yield per animal and is the most decisive factor because it ranges over several orders of magnitude. Although production systems differ significantly,⁸ the choice of animal product is, therefore, even more

extremely low moral value, their small body size leads to a large number of affected animals. It may seem counterintuitive that a very small amount of suffering across a large number of individuals can outweigh extreme suffering across a small number of individuals, but this is an issue well-known to philosophers and termed the repugnant conclusion.²³ Indeed, the same theory leading to the repugnant conclusion underlies well-established human health impact assessments using disability-adjusted life years.²⁴ Nord²⁴ explains that “a disease causing 100 deaths, each associated with a loss of 10 life-years, is as undesirable as a disease causing 5000 people to live in [a] state [with a disability weight of 0.2, i.e. a low impact on life] for 1 year ($100 \cdot 1 \cdot 10 = 5000 \cdot 0.2 \cdot 1$).” The repugnance may arise from scope insensitivity, i.e., a cognitive bias in processing large numbers.²⁵ Attempts to avoid the repugnant conclusion lead to even more counterintuitive conclusions.²⁶ For example, we could avoid the repugnant conclusion by considering average utility instead of total utility (here negative utility to represent suffering). However, this would then lead to what philosophers term the sadistic conclusion: starting with a high average suffering (e.g., 100 lives with an average utility of -1), it would be better in some circumstances to add many lives with a small amount of suffering (e.g., 50 lives with an average utility of -0.1) than to add a few lives with a small amount of net happiness (e.g., 10 lives with an average utility of $+0.1$), as the

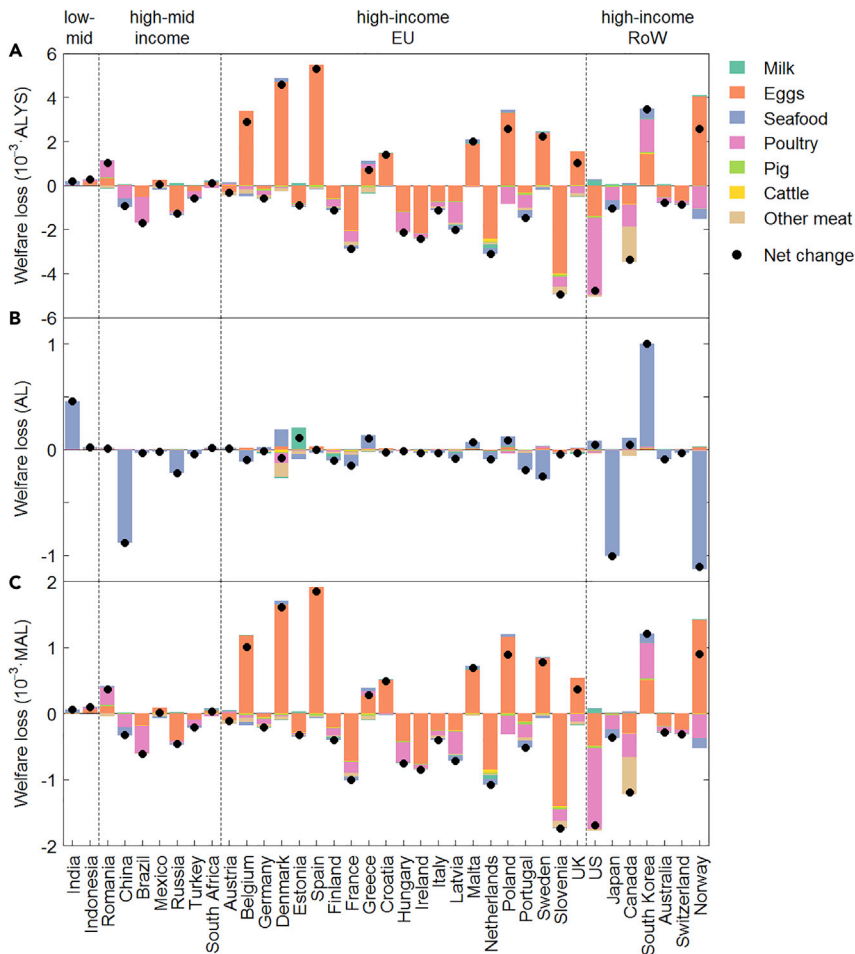


Figure 3. Differences in Animal Welfare Loss between Current Average and Nationally Recommended Diets per Person per Day

Animal welfare loss is expressed in (A) animal life years suffered (ALYS), (B) loss of animal lives (AL), and (C) loss of morally adjusted animal lives (MAL). See also Figure S3 for environmental impacts. The raw data associated with this figure are available in Data S1.

imal welfare (Figure 3). Across countries, the most significant improvements arise from a reduction in the consumption of poultry (for ALYS and MAL) and seafood (for AL), while an increased egg (for ALYS and MAL) and dairy product (for AL) consumption impairs animal welfare the most.

By welfare loss in AL, diets worsen most in Estonia, India, and South Korea. The latter two see notable increases in seafood consumption. Because of opposite trends, i.e., a significant reduction in seafood consumption, animal welfare improves most for Chinese, Japanese, and Norwegian diets. In South Korea, poultry dominates, while eggs dominate in Denmark and Spain. Canada, the United States, and Slovenia improve animal welfare the most with their dietary changes. In Canada and the United

former would have a larger effect on reducing average suffering (average utility of -0.7 compared with -0.9). Due to such a failure of other theories to avoid the repugnant conclusion, we accept it.²⁶ Although some argue that it is impossible to find any satisfactory population ethics,²⁷ others argue that the so-called repugnant conclusion is not repugnant after all.²⁸

Countries with notably high impacts include the United States, Canada (among the top three for ALYS and MAL), China, Japan (for AL), and Norway (all indicators). As an example, in China, 2.4 AL are lost per person per day. With an average life expectancy in China of 75 years in 2011,²⁹ this results in almost 65,000 AL per human life or 28 MAL per human life. Over an average lifetime of 79 years,²⁹ this amounts to even 119 MAL per human life in the United States.

In contrast, India (for ALYS and MAL), Romania (for AL), Indonesia, and South Africa (all indicators) cause the lowest animal welfare loss through their diets (Figure 2). Three of these four countries are also identified as countries with relatively low animal product consumption in general, while Romanians consume little seafood, which limits dietary impacts in terms of AL.

Animal Welfare Associated with Dietary Changes

Although 27 countries reduce their animal product consumption, only 21 (for ALYS and MAL) to 25 (for AL) countries improve an-

imal welfare (Figure 3). Across countries, the most significant improvements arise from a reduction in the consumption of poultry (for ALYS and MAL) and seafood (for AL), while an increased egg (for ALYS and MAL) and dairy product (for AL) consumption impairs animal welfare the most.

Synergies and Trade-offs with Human Health and Environmental Sustainability

There are synergies between all three categories—animal welfare, nutritional quality, and the environment—and all indicators for 7 out of the 37 countries (Figure 4). All categories improve in six countries, including Australia, Brazil, Ireland, Japan, Portugal, and Slovenia. In contrast, everything worsens in South Korea despite already high consumption of animal products in the average diet.

Although there are synergies between animal welfare and nutritional quality in 16 countries, 21 countries face trade-offs. Although dietary guidelines aim to improve human health, intriguingly, a few countries decrease their score of the NRF index, namely Sweden, Latvia, South Korea, and Turkey. Turkey's NRF reduces, i.e., its nutrient deficiency increases, the most (+27%). The contents of many vitamins (especially vitamins A and C) decline in the Turkish recommended diet, while the

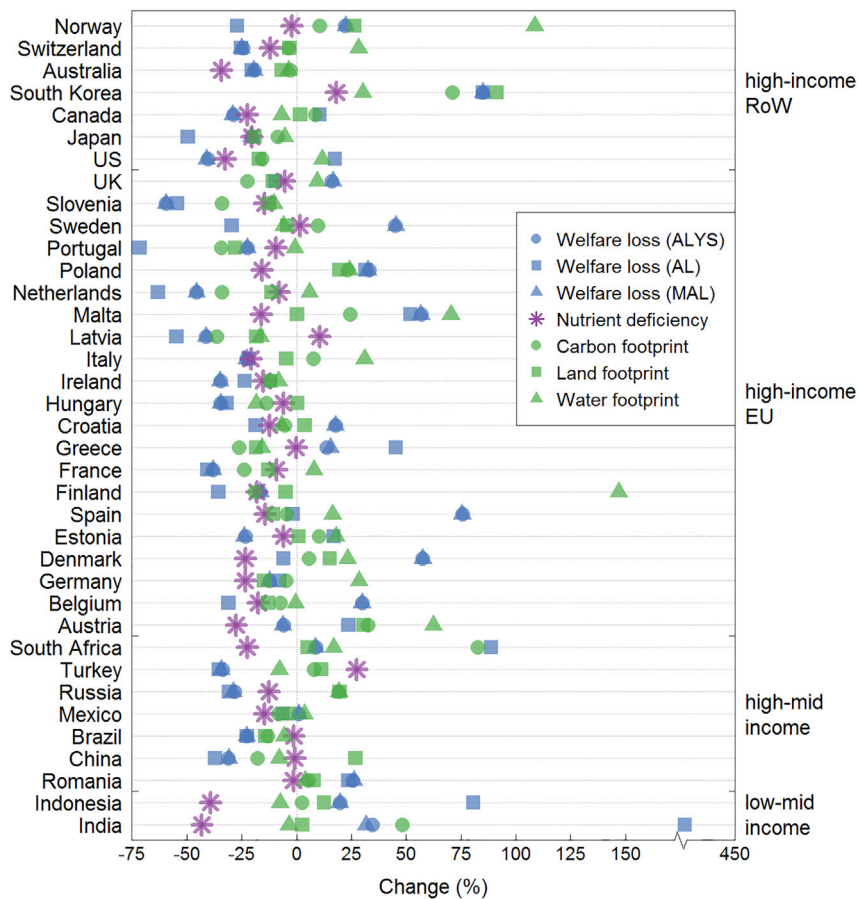


Figure 4. Relative Changes in Nutrient Deficiency, Environmental Impacts, and Animal Welfare Loss

Negative values indicate improvements and positive values indicate deteriorations in impacts.

nationally recommended diet and current average diet as an unweighted average of the 37 countries is also always negative (i.e., it improves), except for again the water footprint. The changes in indicators are mostly statistically insignificant. However, there is sufficient evidence for improvements in nutritional quality and AL across the 37 countries when following dietary guidelines, but also for impairments in the water footprint (Table 1). The increase in the water footprint is highly correlated with an increase in nut consumption (Pearson's $r = 0.83$, $p < 0.01$). We will now discuss how the win-win-win between human health, environmental impacts, and animal welfare can be made more prominent by dietary strategies that have fewer or reduced trade-offs.

DISCUSSION

Nutritional Quality

The key interaction between nutritional quality and other categories is the extent to which a plant- and fungi-based diet is followed. For many different reasons, some consumers decide to completely abstain from animal products, while others are concerned that it would affect their health. Plants can provide sufficient proteins, but their quality and digestibility are often disputed. The deficiency of some plants in specific amino acids can, however, be compensated by dietary mixtures. The major difference between meat-based and vegetarian diets is the lysine content, which is low in cereals. In contrast, legumes such as soy beans are rich in lysine, but deficient in sulfur amino acid which, in turn, is rich in cereals. Likewise, digestibility varies among plants. Although it is low for some cereals, such as millet and sorghum, it is, for example, high in wheat gluten, wheat flour, and soy isolates.^{30,31}

Animal-free diets can potentially be vitamin-deficient in iron, zinc, omega-3, vitamin D, and vitamin B12.³² However, plant- and fungi-based diets are often rich in vitamins which facilitate the absorption of iron and zinc (e.g., vitamin C for iron), resulting in similar risks of deficiency for vegans and omnivores. In contrast, animal products are rich in both beneficial and harmful nutrients, such as saturated fats and cholesterol, increasing the risk for several diseases and mortality. White meat, such as poultry, is rated as healthier than red meat, such as pork and beef. In particular, processed red meat should be avoided.³³

The key question is whether a healthy diet can be composed which limits animal products, particularly red meat, eggs,

amount of saturated fatty acids increases. The largest source of saturated fatty acids in the current average diet is milk, the consumption of which further increases in the recommended diet. The largest sources of vitamin A are vegetables other than tomatoes and onions, and the largest sources of vitamin C are tomatoes, oranges and mandarins, and other vegetables. However, the consumption of both vegetables and fruits reduces in the recommended diet. Turkey's trend in nutrient deficiency (+27%) disagrees most strongly with alleviation in animal welfare loss (-34%, for MAL). Spain faces an opposing trade-off with nutrient deficiency decreasing significantly (-14%), which contrasts most strongly with increasing animal welfare loss (+76%, for MAL). India's nutrient deficiency reduces the most (-43%). Although limiting nutrients increase, especially cholesterol (e.g., contained in meat), many vitamin contents increase as well, most notably vitamin B12 (e.g., contained in milk) and vitamin D (e.g., contained in freshwater fish).

Trade-offs between animal welfare and the environment (Figures S2 and S3) occur similarly often, in 25 countries. For example, animal welfare improves in Russia (-29%, for MAL), while the carbon, land, and water footprints (+19%–20%) increase, mostly due to increased plant-based food and dairy consumption.

Overall, most country's national recommendations improve on average diets according to any indicator, except for the water footprint (Table 1). The difference in impacts between the

Table 1. Cross-Country Comparison of Average and Nationally Recommended Diets

Indicator	Difference	Improvements	Impairments	p Value
Animal welfare loss (ALYS)	-0.00020	21	16	0.46
Animal welfare loss (AL)	-0.070	25	12	0.047 ^a
Animal welfare loss (MAL)	-0.000071	21	16	0.47
Nutrient deficiency	-2.4	33	4	<0.01 ^b
Carbon footprint (kg CO ₂ -eq)	-0.056	21	16	0.38
Land footprint (m ² -eq)	-0.065	20	17	0.19
Water footprint (m ³ -eq)	0.012	17	20	0.026 ^a

The p value refers to the Wilcoxon signed-rank test.

^aIndicates significance at 0.05.

^bIndicates significance at 0.01.

poultry, and, depending on the ethical perspective and valuation of premature death, animal-based seafood. In short, it is eminently possible. We focus on the nutrients of concern, omega-3, vitamin D, and vitamin B12. Omega-3, while mostly obtained from fish oil (it is not contained in meat), can also be obtained from some seed oils (at a lower efficiency) and above all from marine algae, also known as seaweed.³⁴ Both algae and seed oils are novel food sources of omega-3 and require further research to improve the efficiency and sustainability of its production. Because fish alone is not sufficient to meet global demand, and that fish scores high on AL, both alternative sources are needed. The omega-3 intake in any diet, including those with meat consumption, is often suboptimal.³⁵ Likewise, vitamin D deficiency prevails globally. In countries without exposure to sunlight throughout the year and with limited fish consumption, it is important to fortify staple foods with vitamin D. Fortification is typically applied to dairy and non-dairy milk, such as soy and rice milk.³⁶ Significant plant-based sources for vitamin B12 include nori (a seaweed) and tempeh (a fermented soy product). Although the bioavailability of B12 in nori is debated, there is some evidence for it. The content in tempeh depends on the type of bacteria and other fermentation conditions.^{37,38} Again, non-dairy milk is also often fortified with vitamin B12.³² Overall, many presumed nutritional deficiencies in an animal-free diet are misconceptions. From a health perspective, there is significant room to reduce the intake of animal protein, which results in clear animal welfare benefits.

Environmental Impacts

Some studies assess the environmental pressures (e.g., water use) of diets³⁹ instead of the environmental impacts (e.g., water scarcity footprints). Both pressure and impact indicators are valuable and complementary.^{40,41} The choice often depends on the purpose of the study and on data availability. Another choice relates to using environmental impact indicators at the midpoint or endpoint. Endpoint environmental impacts relate to an area of protection, such as human health or ecosystem

quality, and better align with impacts as they are defined in the Driver-Pressure-State-Impact-Response framework.⁴² Again, both types of indicators are valuable.⁴³ We have chosen midpoint environmental indicators because of higher transparency and less uncertainty.

From an environmental perspective, animal products generally far exceed the impacts of vegetable alternatives,⁸ and many studies have shown that the fewer animal products contained in a diet, the lower the contributions to greenhouse gas emissions, land use, water use, and nitrogen and phosphorus emissions, etc.^{9,10,12,15,39} The high water-related impact intensities of nuts are exceptional, and confirmed in previous studies.^{8,44} Therefore, nuts need special attention for defining healthy and sustainable diets. As the variation of water-related impact intensities among nuts is also high,⁴⁵ there is room for improvement despite a recommendation to increase nut consumption in several national guidelines used here and in the EAT-Lancet diet.¹

Animal products are most harmful to the environment and most inefficient in food provision when crops are grown for feed. However, omitting animal products completely from human diets is probably an inefficient use of natural resources. Ruminants, such as cattle, can be raised on land unsuitable for crop cultivation, and livestock generally can be fed with co-products from crop cultivation and the food industry which are inedible for humans and would otherwise be wasted.⁴⁶ If all consumers followed a vegetarian diet which allowed for some animal products, such as milk and eggs, but not for meat, this might also lead to inefficiencies due to co-products in livestock production systems.⁴⁷ Cows, for example, can only continuously provide milk by frequently giving birth. Many bobby calves are slaughtered at the age of just a few days and are considered a waste product. They can provide meat, although much less than cattle raised for beef production. When fertility has reduced past economically sufficient levels, the dairy cow itself can also provide meat when it is slaughtered. Likewise, spent laying hens can provide meat at the end of their life.¹¹ The quantities of animal products available for human consumption under such boundary conditions would be a fraction of the current meat consumption. Realizing these environmental benefits would imply an immense reduction of animal product consumption at least in Western diets. A thorny trade-off that requires further optimization is that some products such as eggs (and seafood) are often used as alternative protein sources in vegetarian or low-meat diets, but score relatively poorly on animal welfare indicators.

As our results show, national dietary guidelines often lead to trade-offs and compromises between nutritional quality, environmental impacts, and animal welfare. Many countries, especially low-income countries, do not even provide any dietary guidelines, and those who do (83 out of 215) rarely integrate sustainability considerations (4 out of 83).⁴⁸ Given the trade-offs and increasing public concern for the environment and animal welfare, it would be highly advisable to offer dietary guidelines with well-optimized options which minimize these impacts where possible.

Research Agenda

Integrating animal welfare assessments into large-scale sustainability assessments is at an early stage and requires further

research. Because of a lack of data at such a large scale, several simplifying assumptions had to be made. Several aspects could improve future large-scale animal welfare assessments, and require a global and interdisciplinary effort. It would be especially valuable if animal (livestock) and fish scientists could provide better data on living conditions and their effects, if population ecologists could provide better data on life expectancies, and if neurobiologists could provide better data on the number of (cortical) neurons. Instead of neurons, animal and fish scientists might also be able to recommend a better proxy for moral values with available data. In addition to improving estimates of already assessed products, it would also be important to increase the coverage of products by animal species, production system, and country with the help of inputs from animal and fish scientists, while industrial ecologists simultaneously improve the resolution of food products (for animal products, see Table 2) and regions in EXIOBASE or multi-regional input-output models in general. Environmental impacts vary greatly for the same products from different regions⁴⁹ and among products.⁸ Recent comparisons of physical trade matrices with high sectoral and spatial resolutions but truncated system boundaries, and multi-regional input-output models with lower resolutions but complete system boundaries have shown that the two approaches lead to different and possibly even opposing results.^{50,51} Approaches to link databases of different resolutions, classifications, and units have been developed,^{52,53} and can be used to achieve a synergy. A prominent attempt to link FAOSTAT with EXIOBASE is the FABIO model.⁵⁴ Finally, a collaboration with moral philosophers would allow to refine the indicator framework. They could advise on alternative moral frameworks, which could potentially avoid some of the counterintuitive conclusions encountered in our work, especially with regard to the interspecies comparison. Alternatively, they might be able to better defend the moral framework we used to increase its acceptability. Besides, they could provide their perspectives on if and how possible benefits should be accounted for. This could play a role where an animal might live on a farm with high welfare standards which grants a better life than in the wild. Still, the current analysis is valuable as a starting point to contribute to the topical debate on sustainable diets and to raise more awareness of animal welfare.

Linking FAOSTAT with EXIOBASE to achieve higher product and region resolutions would also benefit the environmental assessment. As already in the current version of EXIOBASE, creating the environmental extensions for emissions and resource use to match the aspired higher resolutions of the input-output database requires a multi-institute and multidisciplinary effort with experts in input-output modeling, air emissions, land use, and water use.⁵⁵ The necessary environmental data are partly already available at a higher resolution. For example, both the water footprint network and the life cycle assessment community provide product- and country-specific estimates of crop water use.^{49,56}

Epidemiologists could make valuable contributions to improving the nutritional assessment. While this study considers a large number of nutrients, namely 20 (Table 3), the number could be further increased, as reference daily values (RVs) for more nutrients become available. Moreover, this study does not consider the dietary context, for example, nutrient interac-

tions such as the bioavailability of one nutrient depending on the presence of another nutrient, as almost no study does. As Hallström and colleagues⁵⁷ point out, this aspect requires further research efforts.

Conclusion

Human consumption of animal products is a significant source of global warming and dominates land and water use globally. To satisfy Western-style diets, tens of thousands of animals are killed per human during his or her lifetime. Morally adjusting the value of these lives, this is the equivalent of a few dozen humans. Our evidence suggests that for all three aspects—human health, the environment, and animal welfare—a win-win-win can best be realized by strongly reducing animal product consumption. Moving diets toward national dietary guidelines appears to be a good initial step. These guidelines often imply a reduction in animal product consumption and are generally beneficial for all three categories compared with the average diet of the 37 analyzed, mostly Western countries. Yet, our analysis also shows that there are considerable trade-offs. For example, eggs, often used as an alternative protein source in vegetarian or low-meat diets, perform relatively poorly in terms of animal welfare. Furthermore, the water footprint as part of the environmental category is rather impaired across the 37 countries. This highlights the need to further optimize the recommended diets with the objective to minimize such trade-offs. Several countries (Australia, Brazil, Ireland, Japan, Portugal, and Slovenia) have demonstrated that it is possible to achieve beneficial synergies across all three dimensions—human health, the environment, and animal welfare. Adoption of these synergistic diets would imply significant shifts in dietary habits, but even though these diets would be individually and collectively beneficial, society has been slow to react. One reason for that is speciesism, the attribution of less moral worth to some species than others. These attitudes even hold when taking into account beliefs about the species' intelligence and sentience.⁵⁸ In addition, social norms might strongly influence dietary habits.⁵⁹ A minority group can suffice to overturn established behaviors and drive an entire social shift over a tipping point.⁶⁰ Policies can further foster dietary changes by changing people's expectations of others' dietary habits without trying to influence their normative values.⁵⁹ This might, for example, be possible by offering more plant- and fungi-based meals in public canteens. At the same time, although people's moral boundaries might narrow again under stress,⁶¹ they are generally expanding over time.^{3,4} Hence, speciesism might reduce in the future and more people might grant animals moral concern, offering more scope for further demand-side changes in food systems and leading to a win-win-win in health, environmental, and animal welfare outcomes of diets.

EXPERIMENTAL PROCEDURES

Diet Compositions

FAO food balance sheets⁶² provide information on national food supply, encompassing 88 product groups. To obtain the national food consumption, i.e., the average diet, consumer waste was subtracted based on waste shares, distinguishing seven food groups and seven world regions.⁶³

National institutions, such as governmental organizations and nutritional societies, give dietary advice (see Table S1 in Behrens et al.¹⁵). Quantities are mostly expressed in grams, but some differ (e.g., milliliters of milk assumed

Table 2. Linking Animal Welfare to EXIOBASE

EXIOBASE Category	Products with Animal Welfare Assessments
Cattle	Beef
Pigs	Pork
Poultry	Chicken, eggs
Meat animals nec	Sheep meat
Animal products nec	Eggs
Raw milk	Milk
Fish and other fishing products	10 seafood products
<i>Wool and silkworm cocoons</i>	<i>Salmon</i>
	<i>Shrimps</i>
	<i>Insects</i>

For products presented in bold, an animal welfare assessment was still needed. Products and categories presented in italic were disregarded.

to be equivalent to grams, number of eggs, servings, etc.) and were converted to grams.⁶⁴ The 88 product groups from the FAO were assigned to the broader food groups of such guidelines to link the two data sources. Note that the dietary guidelines are not always the latest version, as our analysis required food-specific recommendations (this concerns, e.g., Brazil). Where guidelines provide choices between broad food groups (e.g., meat or fish), quantities were split proportionally to the average diet. If guidelines disregard some food groups, consumption of the respective products would remain unchanged compared with the average diet. These two assumptions minimize the dietary changes that would be required by consumers. The resulting nationally recommended diets were then scaled to the calorie intake of the average diet, i.e., both diets are isocaloric. Only empty calories (sugars, stimulants, alcohol) and butter were excluded from upscaling, as they are recommended to be limited, and spices were excluded from any scaling. In an isocaloric diet, spices are unlikely to change, as they fulfill taste rather than nutritional purposes.³⁹

Further details on the diet constructions are described by Behrens et al.,¹⁵ upon whose work the diet constructions in this study built.

Multi-regional Input-Output Analysis

Impacts were derived from consumption-based accounting. We used an extended multi-regional input-output database, EXIOBASE v.3.4⁵⁵ (free and open access, available at www.exioibase.eu/). It describes the economic linkages between 44 countries, five rest-of-the-world regions, and 200 product categories for a time series from 1995 to 2011, while this study focuses on the most recent year. Among the 200 product categories, 12 relate to food and the 88 food products from the diets described in the previous section were each assigned to one of them. Because the food in FAOSTAT and national dietary guidelines is expressed in physical units, while the final demand in EXIOBASE is expressed in monetary units, the conversion requires food prices. These were derived for each country or region by comparing the final demand in EXIOBASE with the food supply in FAOSTAT, which was originally used to feed the agricultural sectors within EXIOBASE.

The database contains a large number of extensions for environmental pressures, among which we focused on greenhouse gas emissions, land use, and blue water consumption (surface and groundwater). These were translated to environmental impacts, namely carbon footprints (CO₂-equivalents) using global warming potentials at a 100-year time horizon,⁶⁵ land footprints (m²-equivalents) using land stress indices,⁴⁹ and water scarcity footprints (m³-equivalents) using water scarcity indices.^{45,66} Land stress indices weigh land use based on an area's potential net primary production of biomass and are rescaled such that they range from 0 to 1.⁴⁹ Water scarcity indices relate to the water consumption-to-availability ratio and are rescaled by a logistic function such that they also range from 0 to 1.^{45,66} Carbon footprints are well-established, and weighted land and water use are consistent with them, as all three convert pressures by emissions or resource use into environ-

mental equivalents. This is also consistent with the newly created animal welfare extension described in the next section, which considers impacts on animal welfare and not merely consumption volumes of animal products. For water footprints specifically, the International Organization for Standardization (ISO) developed guidelines (ISO 14046) and recommends to consider the potential environmental impacts and not merely the volumes of water used,⁴¹ as the blue water footprint defined by the water footprint network does.⁶⁷ Although water footprints of the water footprint network would highlight which dietary changes would save the most water, water scarcity footprints as used here highlight which dietary changes most reduce water-related environmental impacts. Saving water is important for reducing water scarcity, but local information on water scarcity is important to assess and ensure the environmental benefits of saving water, as water is not globally but locally scarce due to the uneven distribution of water availability and demand.⁴⁵

Impacts (H) were calculated with the Leontief model:

$$H = B \cdot (I - A)^{-1} \cdot F \quad (\text{Equation 1})$$

F is the final demand of food for a diet with 9,800 rows (49 regions and 200 products of which 25 are related to primary or derived food products, encompassing seven animal food categories) and 37 columns representing the countries for which we analyze the diets. A is the technical coefficients matrix, I the identity matrix, and $(I - A)^{-1}$ is called the Leontief inverse, all with 9,800 rows and columns. B is the extension with six rows for the impact categories mentioned above (three for the environment and three for animal welfare) and again 9,800 columns. The calculation was performed twice: once with F representing the average diets of the countries and once with F representing the nationally recommended diets. The difference between the two was then taken as the change in the dietary impact.

Some crop categories are too aggregated and encompass crop groups which highly differ in their land and water footprints, namely “vegetables, fruits, and nuts” and “crops nec” (not elsewhere classified). Therefore, we calculated their impact changes based on the impacts of the average diets and impact-weighted average relative changes in diets. We distinguished vegetables, fruits, and nuts, as well as potatoes, legumes, stimulants, spices, and other crops nec. As impact weights, we used global production-weighted average land and water footprints^{49,66} of these crop groups.

Animal Welfare

An animal welfare extension was added to EXIOBASE, following the animal welfare assessment framework of Scherer et al.¹¹ and reusing some of their indicator values. EXIOBASE contains eight product categories relevant to animal welfare (Table 2). Because wool and silkworm cocoons are not related to diets, they were disregarded in this study. After pig, chicken, and cattle meat, sheep meat has the largest production volume in the world.⁶² Therefore, sheep served as the representative of meat animals nec. Salmon was replaced by more representative fish and seafood, such as the Peruvian anchovy as a common species from capture production and the grass carp as a common species from aquaculture production.⁶⁸

The welfare of sheep and aquatic animals still had to be assessed and followed the framework of Scherer et al.¹¹ Besides the conditions during farm life and slaughter, it considers the animals' lifetime and the number of animals affected. Three alternative indicators represent different ethical perspectives and differ in how they value premature death. Indicator 1 expresses animal welfare loss in ALYS and disregards premature death, as animals who suffer might prefer a short life to end the suffering. ALYS essentially multiply the number of animals directly or indirectly consumed for a specific diet with a relative measure for their suffering (ranging from 0 to 1) and the duration of suffering, irrespective of the animal and not normalized to an expected lifespan. Because animals ultimately strive to survive, indicator 2 expressed in AL distinguishes lives lost and lives with disability (i.e., lives suffered), in line with the disability-adjusted life years concept for human health. Here, the indicator counts the ALYS and animal life years lost across all animals related to a specific diet normalized to their life expectancy, i.e., accounting for premature death. Indicator 3 gives different weights to premature death (lives lost) of animals based on their degree of self-awareness and their sense of time, and expresses animal welfare loss in MAL. In the MAL, the moral value of an animal life is based on the number of (cortical) neurons of the specific type of animal,

Table 3. Reference Daily Values for Macro- and Micronutrients

Nutrient	Reference Daily Value	Reference
Nutrients to encourage		
Proteins	10 E% ^a	82
Fats	20 E% ^a	83
Calcium	750 mg	84
Fibers	25 g	81
Folates	250 µg	85
Iron	11 mg	86
Vitamin A	530 µg	87
Vitamin B1 (thiamine)	0.3 mg/1,000 kcal ^a	88
Vitamin B2 (riboflavin)	1.2 mg	89
Vitamin B3 (niacin)	5.5 mg/1,000 kcal ^a	90
Vitamin B6	1.4 mg	91
Vitamin B12 (cobalamin)	4 µg	92
Vitamin C	85 mg	93
Vitamin D	15 µg	94
Zinc	9.5 mg	95
Potassium	3,500 mg	96
Magnesium	325 mg	97
Selenium	70 µg	98
Nutrients to limit		
Saturated fatty acids	<10 %E ^a	83
Cholesterol	<300 mg	83

^aWe assumed a reference daily calorie intake of 2,500 kcal. %E is the percentage of total dietary energy. We used conversion factors of 4 kcal/g for proteins and 9 kcal/g for fats.

compared with that of humans, and where this information is missing, the moral value is approximated by the relative brain mass. This indicator would count one MAL as equivalent to a loss of a human life.¹¹ The score on ALYS and AL is hence low if food is provided by fewer (and hence bigger) animals. The MAL additionally corrects for the complexity of the life form, which usually is higher in bigger animals.

Since EXIOBASE distinguishes live animals and processed animal products, animal welfare loss was calculated per kilogram live weight. Moreover, we did not consider monetary value fractions for allocating impacts in case of by-products, as done in Scherer et al.¹¹ For instance, cattle deliver both beef and leather, but in EXIOBASE such an allocation is performed automatically, as part of the monetary output flows from cattle rearing to food products from cattle and another to leather and leather products. The animal welfare loss by product and production system represents the Q matrix in the input-output model (in Equation 1 integrated into B).

The life quality of sheep was assessed in analogy to cattle based on the number of days per year on pasture.⁶⁹ The moral value was derived from the moral value of cattle (both belong to the same family Bovidae), and by comparing their brain weights.⁷⁰

For seafood, we calculated production-weighted averages of the five most common animal products for either capture or aquaculture. The welfare loss of aquatic plants was assumed to be zero, and their share at the global level reduced animal welfare loss of seafood. Fishes were assessed similarly to salmon but with different product yields⁷¹ and life expectancies.^{72,73} Although the life quality of farmed salmon in the previous study was assumed to be unaffected (equal to 1 out of a range from 0 to 1) due to a sufficiently low stocking density, here we assumed that the life quality of farmed fishes varies between 0.9 and 0.99 and was differentiated based on the FishEthoScore.⁷⁴ The score measures the likelihood of fish welfare under minimal farming conditions and is based on 10 ethological criteria, from which we disregarded slaughter as the tenth criterion because we assessed slaughter separately from conditions during farm life. Besides the relative brain size, the moral value of fishes also con-

siders that the telencephalon covers a smaller part of the brain than in a human being.⁷⁵

Among the five most common aquaculture products is the Manila clam, a bivalve. It was treated similarly to insects. The moral value was derived from the number of neurons. Based on the lower number of neurons from two gastropods and its number of ganglia compared with that of bivalves,¹⁸ we assumed the Manila clam to have 7,000 neurons. Its moral value is about 20 times lower than the average of the two insects analyzed by Scherer et al.¹¹ In line with that, we also assumed the reduction in life quality to be 20 times lower and set its life quality to 0.99995.

Although raw data availability did not allow us to distinguish the animal welfare of products and production systems by country, we considered different shares of production systems by EXIOBASE region. Steinfeld et al.⁷⁶ provide the production of several animal products in different production systems at the global level and for the developing world. We derived the shares thereof and disaggregated them to EXIOBASE regions based on the deviation of regional area shares from the area shares for the globe or the developing world. The area shares were obtained by applying zonal statistics to the spatial distribution of livestock production systems.⁷⁷ FAOSTAT⁶² provides national production quantities of livestock products. The production quantities of meat were converted to production quantities of live animals based on the dressing percentages, i.e., carcass weight per live weight.⁷⁸ For seafood products, the national production quantities from either capture or aquaculture in 2011, the most recent year available in EXIOBASE, were extracted from FAO's FishStat.⁶⁸ The production quantities by EXIOBASE product and region represent the B matrix in the input-output model.

Nutrient Quality

The nutrient quality was assessed with a NRF index, modified from the proposal by Fulgoni and colleagues.²² The index takes the ratio between the nutrient content and a reference amount. It considers both nutrients to encourage and nutrients to limit. We used the percent reference DV as the reference amount and capped nutrients at 100% DV. The capping avoids overvaluing foods that provide a lot of a single nutrient and constrains the index to a maximum of 100%. Our index differs in the nutrients we considered and in the DVs. These sorts of methodological choices can affect the results and lead to different conclusions.⁵⁷ For limiting nutrients, we only considered amounts above the maximum DV. The nutrient choice was guided by the European Food Safety Authority (EFSA) (Table 2 in EFSA⁷⁹) as well as the availability of DVs. We considered 20 nutrients in total, and the following 18 nutrients to encourage: proteins, (healthy) fats, calcium, fibers, folates, iron, vitamin A, vitamin B1 (thiamine), vitamin B2 (riboflavin), vitamin B3 (niacin), vitamin B6, vitamin B12, vitamin C, vitamin D, zinc, potassium, magnesium, and selenium. Two nutrients to limit included: saturated fatty acids and cholesterol. Sodium and sugar should also be limited, but were not included because they are mainly added during food preparation and manufacturing.^{80,81} Table 3 lists the DVs.

Since animal welfare loss and environmental impacts are negative aspects of a diet, we converted nutritional quality to nutrient deficiency by subtracting nutritional quality from 100%.

Statistical Analysis

To test if impacts reduced with the dietary changes, we (1) calculated the difference in unweighted averages of the 37 countries, (2) counted how many countries improved and impaired, and (3) performed the Wilcoxon signed-rank test. The Wilcoxon signed-rank test is a non-parametric hypothesis test to compare two dependent samples. If the resulting p value is below 0.05, it indicates that there is a statistically significant shift in the location of the data distribution.

DATA AND CODE AVAILABILITY

The main underlying data sources are publicly available: FAOSTAT (<http://www.fao.org/faostat/en/>) and EXIOBASE v.3.4 (<https://www.exiobase.eu/index.php/data-download/exiobase3>). The sources of the dietary guidelines are described by Behrens et al.¹⁵ (open access) and the animal welfare scores are mostly taken from Scherer et al.¹¹ (open access). The raw data associated with Figures 1, 2, 3, and S1–S3 are available in the Data S1.

A part of the code is based on a modified version of the code available at <https://github.com/PaulBehrens/EvaluatingEnvironmentalNRD>. Other code is available upon request.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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