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Nutrient yields from global capture fisheries could be sustainably doubled through improved utilization and management

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The global food system is facing the challenge of producing sufficient nutrients to accommodate future demands within planetary boundaries, while reducing malnutrition. Although nutrient-rich seafood can play a prominent role in resolving this challenge, seafood from capture fisheries is currently partly wasted. Here we quantified the nutrient contribution from capture fisheries through a hypothetical scenario that assumed all captured seafood and byproducts from seafood processing would be used for human consumption. Our simulations show that available seafood per capita can be doubled without increasing the pressure on global fisheries when all reported, illegal, and discarded capture is used as food, complemented with processing byproducts. In such a scenario, seafood contributes greatly to daily nutrient requirements – e.g., omega-3 can be fully met. Although uncertainty should be considered, these results indicate that putting the whole fish on the table can increase nutrient availability from capture fisheries substantially and sustainably.

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With nearly one in three people having no adequate access to food in 2020 and an increasing rather than decreasing trend in the prevalence of malnourishment worldwide[1], Sustainable Development Goal 2 (to end world hunger and malnutrition in all its forms by 2030) is not within reach. Moreover, the environmental costs of food production challenge the future availability of nutrients to reduce the triple burden of malnutrition. Animal source foods like meat, eggs, dairy and farmed fish, require a large share of global agricultural land and contribute to greenhouse gas emissions, the loss of natural ecosystems, and a decline in biodiversity[2,3]. Nevertheless, these animal foods are a valuable source of the nutrients in highly bioavailable forms and therefore play an important role in achieving food security worldwide[4,5]. Seafood, both wild caught or farmed, is a rich source of nutrients including vitamin B12, D and A, iodine, zinc, selenium, and calcium[6,7]. Eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) are the most potent long chain omega-3 fatty acids for the human body and brain, and these can only be derived from marine sources. In general, seafood provides more nutrients at lower greenhouse gas emissions compared to terrestrial animal source foods[8]. However, nutrients from capture fisheries are currently underutilized for human consumption and thereby wasted, which is in conflict with both Sustainable Development Goal 2 and 14 (to conserve and sustainably use the oceans, seas and marine resources for sustainable development).

Each year, more than 10% (i.e., > 20 million tonnes) of all seafood is produced specifically for other uses than for food – mainly for the purpose of feed (fishmeal and fish oil or bait)[9]. Seafood for feed production mainly comes from wild capture fisheries while species captured for this purpose could play an important role in food security as they are suitable for direct human consumption as well[10,11]. Moreover, 11% of seafood caught annually is discarded; this capture is not brought to land because it is undersized, unsaleable, or otherwise undesirable[12]. Furthermore, most fish is consumed as fillet which results in large volumes of byproducts from processing. Only about one-third of these byproducts, including head, skin, bones and other trimmings, are used as fishmeal and fish oil, while the remainder is used to produce bioenergy or fertilizer, incinerated, or sent to landfill[13,14]. Alternatively, these byproducts could be used for human consumption[15,16]. At the same time, around one-third of global fish stocks that are assessed are currently overexploited[17] which could ultimately lead to declining fish stocks and a lower availability of nutrients from seafood[18]. Illegal, unreported and unregulated (IUU) fishing, which is estimated at 20% of all fish sold[19], increases the risk for overexploitation as it complicates defining sustainable fishing levels and keeping track of compliance to those.

It is increasingly acknowledged - e.g., in line with circularity principles - that to reduce the environmental impact and enhance global food security, catch suitable for human consumption should be used directly and waste avoided[20–22]. We therefore evaluated the maximum utilization potential of global capture fisheries to provide essential nutrients and to enhance global food security. We created an explorative, hypothetical scenario that is embedded within a redesigned future food system in which technologies, regulations and practices are in place that enable a circular approach to nutrient utilization. In this scenario, we put the whole fish on the table by assuming that all capture and edible byproducts are used for human consumption. This No Waste Scenario was compared to the current use of captured seafood (Current Scenario). The results show that available seafood per capita can be doubled without increasing harvest. Moreover, seafood contributes greatly to daily nutrient requirements - e.g., omega-3 can be fully met – and commonly deficient nutrients such as calcium, vitamin D and iron can be largely sourced from byproducts. Putting the whole fish on the table has the potential to greatly enhance food security and to contribute to future sustainable food systems.

Results

Scenarios. Our calculations show that the amount of seafood for direct human consumption could be almost doubled from 49 million tonnes (Mt) in the Current Scenario to 88–109 Mt in the No Waste Scenario (Fig. 1, Table 1), equal to 16.0–18.7 and 31.4–38.8 g per person per day, respectively.

In the No Waste Scenario daily human requirements for omega-3 would be more than covered (108–120%). Moreover, this scenario could contribute to meeting requirements for several other nutrients, with highest contributions to calcium (38–46%), vitamin B12 (27–31%) and selenium (15–17%) (Fig. 2, Supplementary Table 1). In the No Waste Scenario

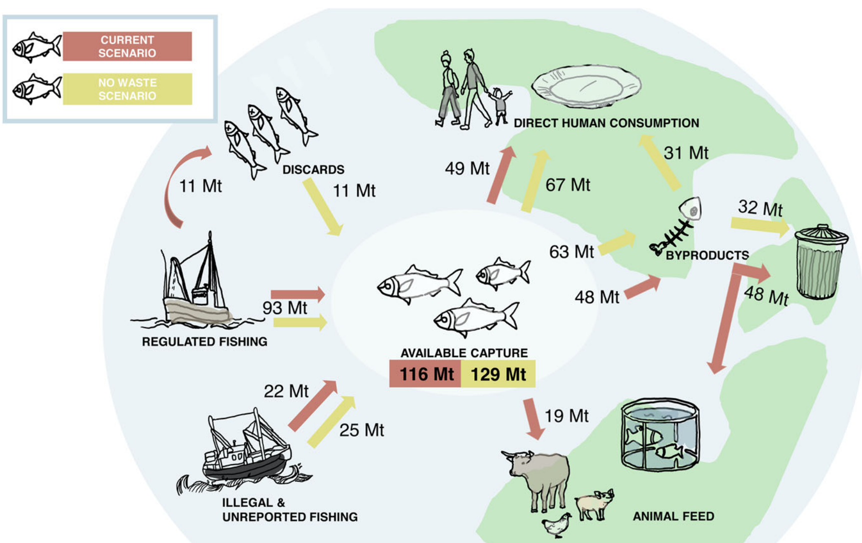

Fig. 1 Visualization of how available capture for human consumption was derived. Arrows indicate to which use fish captures were assigned in each scenario (Current = red, No Waste = yellow). Values indicate how much seafood is available for capture from which source (left side) and how much of this is dedicated to which end-use (right side), values are given in million tonnes (Mt).

there is a relatively larger contribution from pelagic fishes to daily nutrient requirements (Fig. 2, Supplementary Table 2). This results in a higher availability of calcium, iodine, and iron, which are among the nutrients that have inadequate intake levels at a global level[23,24].

Table 1 Available seafood (annual total) in the two scenarios, split by source and end-use.

		Total capture (tonnes)		
Source	Scenario	Value	Lower	Upper
Reported capture	Current & No Waste	93,165	n/a#	
IU fishing†		22,335	13,356	31,271
Discards		11,378	9399	13,946
Discards - IU		2504	1311	4144
Available				
Available capture	Current	115,500	106,521	124,436
	NoWaste	129,382	117,231	142,526
Filleted/shelled equivalent	Current	59,625	54,965	64,261
	NoWaste	66,675	60,408	75,387
Total byproducts	Current	47,579	43,850	51,291
	NoWaste	62,707	56,823	67,139
Edible byproducts	Current	21,622	19,944	23,291
	NoWaste	30,826	27,918	33,870
End-use				
Human consumption	Current	48,890	45,026	52,733
	NoWaste	97,501	88,326	109,257
Other uses (edible)	Current	15,528	n/a#	
	No Waste	0	0	0
Other uses-IU (edible)	Current	3503	2117	4884
Other uses-IU (edible)	NoWaste	0	0	0
Inedible*	Current	25,957	23,906	28,000
	NoWaste	31,881	28,905	33,269

Value Calculated value in 1000 tonnes, *Lower* Lower estimate, *Upper* Upper estimate.
*Includes all parts not suitable for human consumption; †Illegal and unreported fishing; #not available: uncertainty was not considered for the reported capture production and other uses of reported capture production.

Current seafood from global fisheries. In the calculations of available capture, we started from what is captured and brought to land, both reported to the FAO and unreported from IU fishing. From 2015 to 2019, a yearly average of 93 Mt was brought to land and reported with the largest contribution from Asia. Estimated capture from illegal and unreported (IU) fishing was 20–26 Mt, to which Africa contributed the most relative to its reported capture, which is in line with previous reporting that states Africa being the epicentrum of IU fishing[25]. The landed seafood was divided into a filleted or shelled fraction and byproducts, which in the Current Scenario is partly used for direct human consumption (45–53 Mt) and partly for other uses like animal feed, uses outside the food system (not quantified in this study) or disposal (62–72 Mt) (Fig. 1). The approximate 17.5 g per person per day that is available for human consumption in the Current Scenario provides an important share of some nutrients that are mainly sourced from seafood, instead of from other animal source or from plant source foods. The highest contributions are for the requirements for omega-3 (48–57%), vitamin B12 (21–24%), selenium (11–13%), and vitamin D (6–7%).

Fish for food instead of feed. When all seafood brought to land is used for human consumption, instead of partly for other uses, there would be 107–124 Mt for human consumption, instead of 93 Mt. This can potentially increase the daily availability of seafood to 19.6–23.0 g per person and can increase the availability of nutrients up to 49% (based on upper estimate). For example, omega-3 per person per day from 127.6 to 162.6–190.5 mg (equivalent to 66–78% of the daily human requirement). The achieved increases from the Current Scenario differs between nutrients due to additional species added for human consumption that were previously destined for other uses, e.g., more small pelagic fishes previously fished for animal feed (Supplementary Table 2).

Utilize waste during and after fishing. When all currently discarded seafood is used for human consumption in addition to the reported and illegal captures, the capture production can be further increased to 117–143 Mt (60–75 Mt filleted and shelled

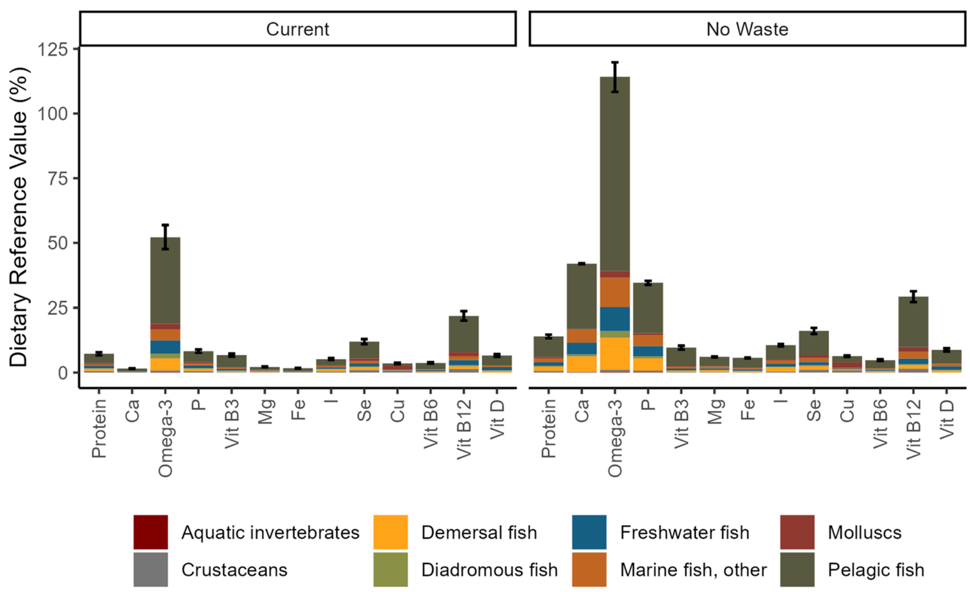

Fig. 2 Contribution to Daily Reference Values (DRV) from different fish species aggregated to seafood groups in the Current and No Waste Scenario in % of DRV. Vertical lines represent the uncertainty range around IU fishing and discards. Ca Calcium, P Phosphorous, Vit B3 Vitamin B3, Mg Magnesium, Fe Iron, I Iodine, Se Selenium, Cu Copper, Vit B6 Vitamin B6, Vit B12 Vitamin B12, Vit D Vitamin D.

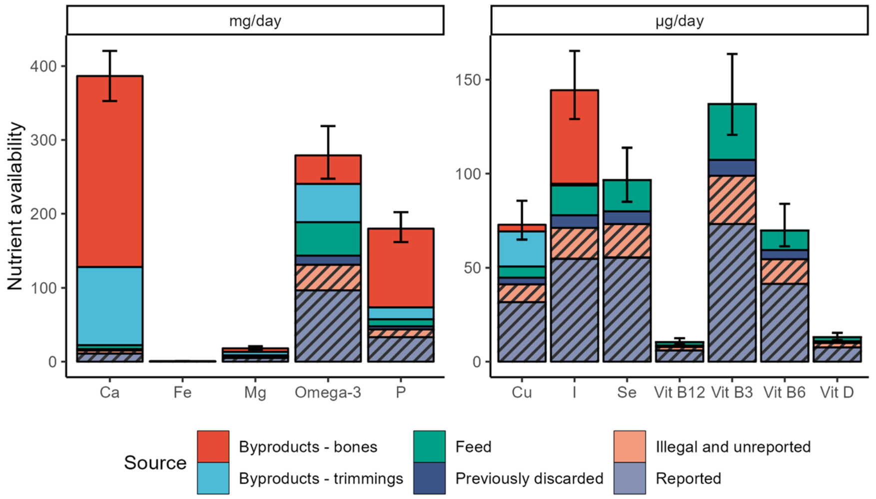

Fig. 3 Amount of nutrients made available in the No Waste Scenario. Colours indicate the source of the seafood, patterns indicate whether it is currently used for human consumption (stripes) or not (no pattern). Vertical lines represent the uncertainty around IU fishing and discards. Ca Calcium, P Phosphorous, Vit B3 Vitamin B3, Mg Magnesium, Fe Iron, I Iodine, Se Selenium, Cu Copper, Vit B6 Vitamin B6, Vit B12 Vitamin B12, Vit D Vitamin D.

equivalent), or 21.5–26.8 g per person per day. Although marginal, this frees up an additional amount of nutrients (Fig. 3). On the other hand, consuming all edible parts of the fish – instead of using the edible byproducts for other purposes – increases some essential nutrients to a large extent. To this regard, we defined edible as anything that would not be regarded inedible, that is, toxic or poisonous to eat. Edible in this sense is therefore not equal to eatable, which describes something with acceptable flavour[26]. The main edible byproducts (i.e., trimmings and bones) can be processed via the extraction and re-incorporation of valuable compounds (e.g., protein, gelatin, chitin), by producing new products from mechanically separated meat (e.g., restructured fish steaks and patés) or by creating food products from the byproducts (e.g., bone flour)[27–29]. Directing these byproducts from the reported, IU and discarded capture to human consumption, increases the total availability of calcium 27-fold, phosphorous four-fold, and iron and magnesium three-fold compared to the Current Scenario. That is, by consuming seafood products made from trimmings and bones, as well as reported, IU and discarded capture (No Waste Scenario), 38-46% of global calcium requirements could be met by capture fisheries compared to 1.5–1.8% in the Current Scenario (Fig. 2). We find that the seafood groups that contribute most nutrients from previously wasted sources are pelagic fishes (Fig. 2).

Consider nutrient distribution. If all capture production would be consumed within the continents that captured the seafood (i.e., that operate the fishing vessels) without being traded, nutrients would be unequally distributed. Our calculations on the continent-level for the No Waste Scenario showed that per capita per day nutrient availability would be lowest in Africa and Asia and highest in Oceania (Fig. 4, Supplementary Table 3). Africa would not be able to provide the daily requirement for omega-3, while Oceania could provide 200%. In addition, the availability of individual nutrients can be relatively high or low, depending on the species caught. For example, vitamin B3 and B6 are relatively high in Oceania due to high capture levels of yellowfin and skipjack tuna. Whereas in Asia, a high capture of mollusks and crustaceans – i.e., eight times higher than in Europe – leads to a high availability of copper. For food security, nutrients should be equally distributed by trade among regions[30], with special attention to those countries with no direct access to fishing waters.

Discussion

Our results show that in a scenario in which all captured seafood that is captured is used for food and the use of edible byproducts is increased, seafood availability can be nearly doubled compared to the current situation (around 34.2 g per person per day compared to 17.5 g). This scenario should be interpreted as an exploration of the potential contribution that wild capture fisheries can make to the food system. although multiple limitations avoid exploiting this potential in the near future.

When seafood previously used as animal feed or other uses is directed to human consumption, the species composition of the total seafood directed to human consumption changes. As a result, unique nutrient profiles from species and byproducts that were not available before are now used for human consumption. This indicates how nutrient availability does not linearly increase with increasing yields – which is in line with previous findings[6]. The fish captured but not used for human consumption are mainly small pelagics that are particularly rich in calcium[31,32]. These fish can be essential in enhancing food security as they are accessible and affordable[10,11,33]. “Encouraging people to eat low-trophic aquatic foods is undoubtedly the prime strategy for using our aquatic nutrient resources more efficiently and mitigating the environmental impacts of food production”, as stated by the UN[10]. In addition to fish brought to land but not used for human consumption, nutrients from discarded fish that are not brought to land are also wasted. However, seafood that is returned to the sea may survive and become part of the ecosystem again. Therefore, the assumption that all fish would die and brought to land would i) risk double counting of discarded fish that can be harvested again after survival and ii) suggest that it is preferable to let all unwanted capture die to be used for human consumption instead of aiming for a higher survival rate. Survival rates of unwanted and discarded seafood depend on many factors – e.g., capture method, species, capture size and environmental factors[34]. More so, there is currently no agreed method to determine survival rates, which leads to a high variability in study results[35]. And even when survival at the point of discarding is high, delayed mortality may still occur[36]. Thus, there was no reliable data to apply to our dataset and 100% mortality was assumed in the No Waste Scenario. The effect of assumptions around discards on the results were tested in a sensitivity analysis (Supplementary Discussion 2). This showed that including conservative estimations for survival rates of

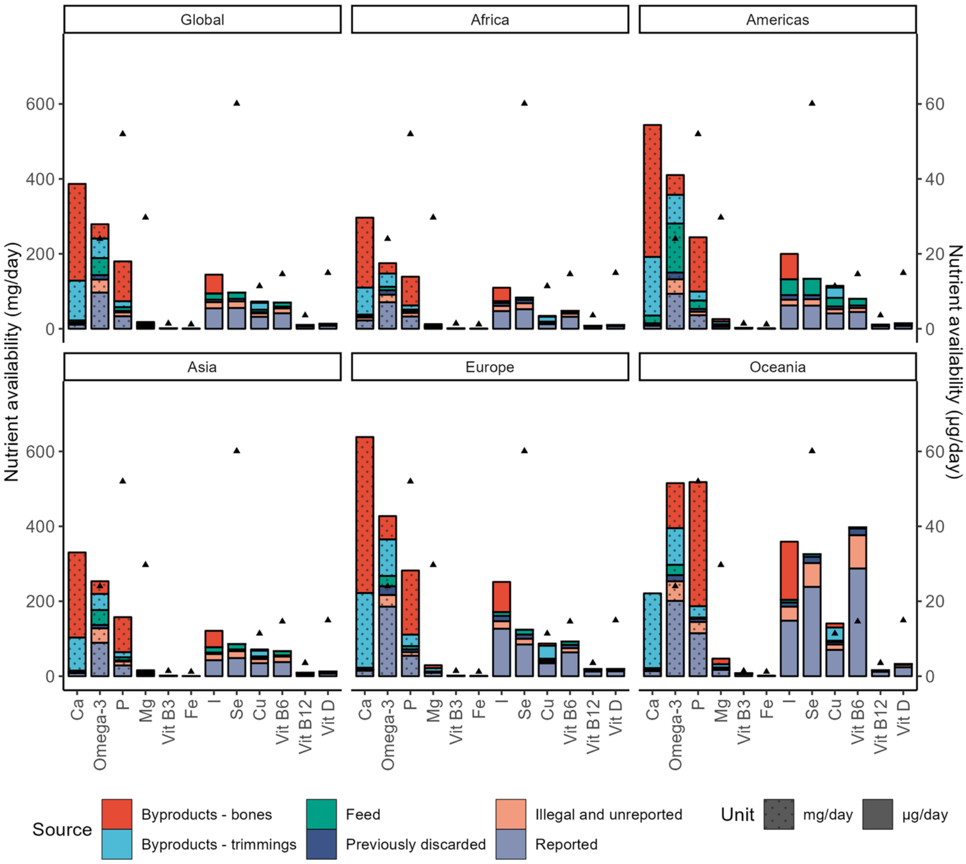

Fig. 4 Nutrient availability per person per day in the No Waste Scenario, per continent. Colours indicate the source of the seafood, patterns indicate the unit used (dots = mg/day, no pattern = µg/day), black triangles indicate the Dietary Reference Value for each nutrient.

discards would decrease edible capture and nutrient availability by only 4%.

Not only nutrients from captured seafood are wasted: several other nutrients from fish bones and trimmings, such as calcium, magnesium and zinc, are highly under-utilized. At the same time, reducing preventable food waste and valorizing non-preventable waste are at the top of the international political agenda and, especially in the EU, the principle of circularity is gaining ground[37,38]. Circularity and circular food systems aim to use resources for human consumption first and avoid waste, or reuse unavoidable waste back in the system[20]. From an ecological perspective, utilizing all nutrients from capture fisheries for human consumption provides space to reduce fishing pressure while maintaining the same nutrient availability as currently. Therefore, our study shows how applying circularity principles to capture fisheries can also be beneficial from an ecological perspective and that it contributes to achieving SDG14: conserve and sustainably use the oceans, seas and marine resources for sustainable development.

Putting the whole fish on the table would require transforming the entire food system, including changes in regulation (e.g., of discard practices and illegal fishing), legislation (e.g., the use of animal byproducts as food), and consumption (e.g., change dietary patterns). For example, it is not straightforward to bring otherwise discarded catch to land, as there is only a limited amount of capacity on a fishing boat[39]. Moreover, because captured fish is used as bait in other fisheries as well as feed in aquaculture and livestock production, these sectors are interlinked[40,41]. Therefore, using the full capture production and edible byproducts for human consumption implies that these sectors are either compromised in productivity or should rely on other sources as feed. In our study, we assumed fisheries that currently rely on bait, can maintain their fishing level by, for example, using artificial bait or lure[42,43]. Moreover, based on estimated bait fractions per fishing country[44], we calculated that less than 1% (i.e., 0.16 Mt) of reported capture is currently used for bait, with high use in some areas but none in most. These calculations could not be verified by other data sources because to our knowledge, no global estimates of bait use are available. From our calculations, however, it can be concluded that continuing current bait use would have negligible effects on global nutrient availability, although accounting for bait use may be relevant in certain regions[41] or for certain taxonomic groups. On the other hand, replacing the feed input in the aquaculture sector sustainably may be more difficult because the use of human edible crops increases food-feed competition and contradicts circularity principles[45,46]. Additionally, using plant source feeds may lead to micronutrient deficiencies for carnivorous farmed fish[47] which could ultimately lower the nutrient density of the fillet[48,49]. This study did not consider aquaculture in the scenarios and therefore the question remains how wild capture fisheries can be supplemented by sources that do not rely on human edible inputs. In this regard, low-input or non-fed aquaculture can be part of the solution[50,51].

Wild capture fisheries play an essential role in achieving SDG2: to end world hunger and malnutrition, in all regions of the world. While nutrients in fish like iron and zinc are more available compared to plant source foods[5], the consumption of omega-3 fatty acids has been shown to lower the risk of non-communicable diseases[52,53]. Dietary guidelines generally recommend eating 150–300 g (i.e., 2–3 servings) fish per week[54], which can be covered globally by the availability of fish in the No Waste

Scenario but not with the current fish use (Current Scenario). For Europe specifically, it was shown that only 13 out of 31 dietary recommendations can be fulfilled by national seafood supplies[55]. We found the second highest daily availability of seafood in Europe which makes it questionable if other national dietary guidelines can be met at all. Moreover, the unequal distribution of production from capture fisheries shown by our continent-level analysis suggests that nutrient availability is not highest in the places where it may be most needed to combat nutrient deficiencies. Capture fisheries may be even more valuable in low- and middle income countries where iodine, vitamin D and iron deficiencies are of concern[56].

The consumption of small pelagics as well as edible byproducts from seafood processing may seem a far cry from current consumption patterns but may be feasible with radical food system changes. Such changes would include a change in quota systems to allow landings for human consumption, a conversion of fishing fleets as well as the development of new markets and products[57]. Also, the potential for human consumption largely relies on evolving techniques to separate a greater fraction of edible products from the whole fish or extract specific nutrients[16,58,59]. To this regard, nutrients may be available for human consumption after extraction and incorporation in novel products instead of through direct consumption of the whole fish or its byproducts. Still, unfamiliarity and negative associations limits the consumption of whole fish or its byproducts[60] and processing techniques to change shape and structure may be required for a higher acceptance rate by consumers[60,61]. We acknowledge that attempts to consume whole fishes or byproducts have had limited success in the past[57] and that this barrier may make it impossible to achieve our explored scenarios. However, the results shown here emphasize the importance of staying invested in the required developments.

For this theoretical exploration of wild captures seafood's potential, we assumed fishing would be sustained at current levels. However, it is increasingly understood that for some stocks, current fishing levels are not sustainable[9], while other stocks are currently underfished[62]. This is why maximum sustainable yield (MSY) levels are being incentivized. Although MSY levels are not a target- but rather a maximum fishing level, fishing at MSY levels can increase the total capture production in the long-term[63]. Therefore, we assessed the impact of better nutrient utilization from global capture fisheries when fishing would be done at MSY levels in Max Sustainable Scenarios (Supplementary Discussion 1). These scenarios take the same approach as the No Waste Scenario while using MSY estimates instead of reported capture production, and either exclude IU fishing and discards (Max Sustainable Scenario) or not (Max Sustainable+ Scenario). The results showed that, because MSY levels would lead to an 11% increase in capture production, nutrient availability would still be increased to 28.2 g per person per day even when IU fishing and discarding practices are abandoned. The latter would be more in line with sustainable fishing practices but underestimates the potential production from wild fisheries because MSY estimates are calculated from current fishing levels[64]. When IU fishing and discards were included, the Max Sustainable+ Scenario showed that total seafood availability could increase to 32.7 g per person per day and 138% of omega-3 requirements could be covered (Supplementary Table 1). Moreover, a larger amount of anchovies, sardines and mollusks could be captured under MSY, contributing to micronutrient availability (i.e., mainly calcium and iron). Putting the whole fish on the table and fishing at sustainable levels should not be regarded as separate pathways to a more sustainable use of our marine resources, but rather be combined.

Although this study relied on assumptions to fill data gaps to a certain extent, it contributes to the current state of knowledge by quantifying the potential nutrient contribution from wild capture fisheries when applying circularity principles. The uncertainty associated with the data was emphasized by presenting the results as ranges rather than exact values. These ranges showed that even at the lower estimates, the availability of seafood can still be increased substantially. However, ranges were exclusively based on upper- and lower estimates provided by the data sources used for the calculations, that is for IU fishing and discards. This does not exclusively cover all uncertainty that is expected for the results, e.g., edible yield and nutrient content is not precise enough for each reported species. To test the sensitivity of using alternative values and data sources for nutrient content and edible yield as well as the amount of fish dedicated to other uses and assumptions around discards, a sensitivity analysis was conducted (Supplementary Discussion 2). The sensitivity analysis showed that, although the results would slightly shift when calculated differently – i.e., −29% to + 35% in nutrient availability – the overall message that nutrient availability can be substantially increased when more fish is used for human consumption still stands when using alternative data sources or assumptions (Supplementary Table 2). Nevertheless, it should be emphasized that, due to poor or non-existing data recording and collection, a high level of uncertainty cannot be avoided in assessments like these. We stress the need for more and more accurate data, especially regarding edible yield and nutrient content, to assess the role of fish in global nutrient security under future scenarios[8].

Sustainable management is key to secure nutrients from global fisheries for future populations[6,63,65] and this goes beyond maintaining capture levels that avoid depletion of fish stocks or the use of fishing gear that limits environmental damage[66]. Instead, incorporating human nutrition goals into sustainable management of global fisheries has potential to tackle malnutrition in all its forms[65,67]. Thus, safeguarding those essential nutrients that can be sourced largely from seafood needs to be prioritized. This would decrease the reliance on products from, and natural resources for, land-based animal production. Given current population growth and increasing food demands, we can no longer afford to waste nutrients. We show that without increasing the pressure on global fisheries, more nutrients can become available to the global population, specifically those nutrients that may be deficient, like calcium, vitamin D and iron. For some regions specifically, this could greatly contribute to nutrient security. Thus, goals for sustainable fisheries' management should be re-defined to include putting the whole fish on the table to contribute to global food security and a sustainable food system.

Methodology

Current Scenario

Current fisheries capture. Multiple databases are available that provide catch and landings data[68–70]. In this regard, the FAO's Global Capture Production database[71] provides data on a species level which was preferred for the aim of this study, that is, to calculate a nutrient contribution from wild captured seafood. FAO distinguishes between landings data and nominal catch data, where the latter comprises whole landings and processed landings converted back to tonnes of live weight. Nominal catch data is thus the live weight equivalent of the landings and is referred to throughout this paper as capture production. FAO provides annual data from 1950 onwards and can be consulted on fish species level, structured in ISSCAAP groups[72]. For this study, we included all species captured in both inland and marine waters and belonging to the following groups, further referred to as seafood: Diadromous fish, Freshwater fish, Marine fish, Crustaceans and Molluscs. Additionally, aquatic animals belonging to the group of Other aquatic animals and known for their consumption, like sea-squirts, sea-urchins and jellyfish, were included[73]. These groups provide the majority (88%) of total food supply from aquatic foods[74]. The remaining 12% of aquatic food supply and its subsequent species were excluded as their consumption is negligible on a global scale (Aquatic mammals) or because they did not match the scope of this study (Aquatic plants). In total, capture production for 2167 unique species were extracted from the FAO Global Capture Production database (Supplementary Table 4). Due to annual variability among species in the capture production, the data from 2015–2019 were averaged. Capture production was extracted by continent and aggregated at a global level.

Illegal, unregulated and unreported fishing. Part of the globally available seafood comes from illegal, unregulated and unreported (IUU) fishing. IUU fishing practices undermine the effort to sustainably manage fisheries as it is not possible to keep track of the quantities fished. Most unreported seafood capture either ends up on the regular market or enters the food system in another way[75,76]. Although the exact quantities caught by IUU fisheries are unknown, it is estimated that 20% of all fish sold has been illegally caught[19]. Thus IUU fishing contributes to global nutrient availability while this is not reflected by the reported capture. Therefore, we complemented the reported capture to include IUU fishing estimates[19]. These estimates do not cover unreported capture and are thus for illegal and unreported (IU) fishing, provided as a fraction of reported capture by major fishing area (Supplementary Table 5). The upper and lower estimates were included in the calculations to provide an uncertainty range in our results. Estimates for the Mediterranean and Black sea and inland waters were not included in the referred publication but multiple authors report that also in these areas IU fishing is a serious threat[77–82]. Therefore, we used the average of all fishing areas (18%) as a proxy for IU fishing in these two unassessed areas. For the Antarctic, IU fishing is only an issue for toothfish and therefore the rate of IU in this region was only applied for toothfish[19].

No waste scenario. The No Waste Scenario builds on the Current Scenario by assuming that all currently reported capture and capture from IU fishing is used for direct human consumption (DHC). Moreover, currently discarded fish and byproducts from fish processing is also directed to DHC.

Estimations from different sources show that approximately 20 Mt of total seafood is used for other uses than DHC[9,17,44]. The FAO's most recent estimation is that 11% (~ 20 Mt) of the total seafood production is for other uses than DHC, which is mainly livestock and aquaculture feed[9]. Because aquaculture itself does not produce seafood specifically to use as feed, this 20 Mt represents 20% of wild capture production, comparable to the 27% estimated elsewhere[44]. All menhaden and sand eel species, as well as Norway pout, were not considered for DHC. This was based on a report[22] that determined 17 out of 21 species reported for fishmeal and oil production as suitable for DHC, while four species (i.e., sand eel, gulf menhaden, Atlantic menhaden and Norway pout) being of industrial grade and generally considered too bony, too oily or unsatisfactory for other reasons[83]. The 17 species deemed suitable for DHC are highly nutritious, small pelagic fish traditionally consumed in different regions around the world[10,11]. To calculate the capture production for other uses than DHC on species level, we applied estimates for reduction fisheries specified by fishing country and fish species[44]. This does include byproducts of fish processing that are currently used for fishmeal and fish oil production. In addition to the reported capture, IU fishing quantities were also corrected for other uses than DHC by applying the same estimates. Besides capture not used for DHC, we calculated an additional source of seafood currently captured but not used for DHC: discards that are not brought to land because it is seen as unwanted or unregulated bycatch. Using a recent FAO publication[12], the amount of discarded seafood was estimated by major fishing area, for both reported and IU capture (Supplementary Table 6). The confidence intervals provided by the FAO[12] were used to calculate the uncertainty range in the No Waste scenario. Subsequently, the upper- and lower estimates presented for the No Waste Scenario were determined by applying upper- and lower estimates for IU fishing[19] to the reported capture and summing this with the upper- and lower confidence intervals for discards[12] applied to the reported capture.

Increased utilization of byproducts. Byproducts from fish processing generally consist of the head, skin, frame/backbone, viscera and trimmings that are largely directed to pet food, livestock feed, and aquaculture feed[84]. Their value for human consumption is reduced due to not fully extracting or mixing these byproducts and edible yield can increase with 21 to 33% if byproducts are well separated and edible flesh is fully removed[15]. For example, the edible yield of Atlantic salmon can increase from 56.2% to 77.1%[15]. All small pelagic fish species can be consumed whole (100% of captured weight)[31,32] which we used in both scenarios to maximize the potential of capture fisheries. However, we excluded all sand eels, menhaden and Norway pout as described in the previous section and assumed that some small pelagic fishes may have to be treated before they can be consumed as whole[85]. For all fish species other than pelagics, we categorized byproducts into head, trimmings, skin (0–31% of total weight, depending on species) and frames (12% of total weight), but excluded viscera (a less edible byproduct)[15] (Supplementary Table 7). Species previously excluded for human consumption (i.e., menhaden, sand eels, Norway pout) were included in the byproducts calculation. No literature was available for food uses of mollusk or crustacean byproducts, although nutrients in the exoskeleton may be used for pharmaceutical, industrial or agricultural purposes[86]. Therefore, we assumed no byproducts from these seafood sources for DHC.

Available nutrients and edible yield. To calculate the total of nutrients available in all the scenarios, the capture production was linked to data from four food composition databases that covered a wide range of fish species (Supplementary Tables 4, 8). The USDA FoodData Central[87], the UK's Composition of foods integrated dataset[88], the Standard Tables of Food Composition in Japan[89], and the Australian Food Composition Database[90] were selected based on accessibility (i.e., available online in English and in a downloadable format), reliability (i.e., included in the International Food Composition table/database directory) and coverage (i.e., cover a wide range of aquatic food items and nutrients). The following nutrients are regarded relevant for assessing the nutrient contribution of seafood: protein, omega-3 fatty acids (EPA and DHA), sodium, potassium, calcium, phosphorous, magnesium, iron, copper, selenium, zinc, iodine, vitamin A, vitamin B1, B2, B3, B6, B9 and B12, Vitamin D and Vitamin E[91]. For these nutrients, the content of the raw, fillet equivalent of 169 entries were collected to compile a dataset of 66 family-specific (e.g., tilapia) and 103 species-specific (e.g., pink salmon) entries and we further refer to this compilation as the composition database (Supplementary Table 8). For presenting the results, a selection of 13 nutrients was made from all nutrients included in the composition database to visualize the most substantial changes. The composition database was further complemented by edible yield fractions for each of the 169 entries, mainly extracted from FAO[92] but supplemented with other data sources as data for some specific species were lacking (Supplementary Table 8). Similar to Golden et al. (2021)[67], we used a hierarchical approach to extrapolate the 169 species in the composition database to the species covered by FAO Global Capture Production database based on the assumption that species belonging to the same family have similar nutrient content and edible yield[6,67,93]. This assumption, that there is an association between phylogenetic relatedness and nutrient content[93] has been used by others[6,67] and due to a lack of nutrient content data on species level, this approach was used. The hierarchy of matching composition database to captured species started with the common name, as this is how species were named in the four food composition databases used to compile our database. If the common name did not match any entry in the composition database and neither a match was found for the scientific name, the species was matched to a composition database entry based on family first, or ISSCAAP group. This way, 53% of FAO taxa could be covered by either common or scientific name, 26% by family and 21% by ISSCAAP group (Supplementary Table 4). In addition, we calculated the average nutrient content and edible yield of all fish, all crustacean and all mollusk species in our composition database and used this to cover the remaining fish, crustaceans and mollusks, respectively, or the ones falling into the miscellaneous groups. Total available nutrients per capita was calculated by applying edible yield fractions to the capture production, multiplying by the nutrient content, and finally dividing by the 2019 population data[94]. The concurrent steps of calculating the total nutrient availability in the Current and No Waste scenarios is summarized by the following equation:

$$\text{Total nutrients available} = \sum_{i=1} \text{catch}_i * F * \text{edible yield}_j * \text{nutrient content}_j \quad (1)$$

With catch being the landed weight converted into live weight (may include reported, IU and/or discards) for each species i included in the FAO Global Capture Production database, F being the fraction for human consumption depending on the amount of catch being directed to food or feed/other uses, edible yield being the % of edible flesh (and byproducts) for each species j in the consumption database, and nutrient content being the nutrient content for each species j in the consumption database.

To interpret the absolute quantities in relation to nutrient requirements, a weighted average of the age- and gender-specific EFSA Dietary Reference Values (DRVs) was used for reference[95] (Supplementary Table 9). Although EFSA DRVs are specified for the EU population and it can therefore be argued whether they are representative of other regions, we chose EFSA DRVs because these reflect detailed nutrient requirements by sex and age group. This made it possible to calculate a global average that reflects these different requirements.

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

Data availability

All data used in this study is publicly available online. Capture production data was extracted from the FAO Global Capture Production database (https://www.fao.org/fishery/statistics-query/en/home). Nutrient content for fish and seafood was extracted from four food composition databases: the USDA FoodData Central (https://fdc.nal.usda.gov), the UK's Composition of foods integrated dataset (https://www.gov.uk/government/publications/composition-of-foods-integrated-dataset-cofid), the Standard Tables of Food Composition Japan (https://www.mext.go.jp/en/policy/science_technology/policy/title01/detail01/1374030.htm), and the Australian Food Composition Database (https://www.foodstandards.gov.au/). MSY data used for Supplementary Discussion 1 was based on previously published literature[62] but provided to us directly by Prof. Ray Hilborn. Data used for calculations of IU fishing, discards and fraction of production dedicated to other uses was taken from published literature of which the references are provided throughout the Methodology section. All key data is provided in Supplementary Data 1 which is also published on FigShare (https://doi.org/10.6084/m9.figshare.24173202).

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Author contributions

R.C. and H.Z. designed and led the research, R.C. collected and analyzed data. W.S. prepared the figures. The following authors analyzed the data and edited the paper: H.Z, W.S., J.M., G.W. and F.Z. All authors contributed to the interpretation of the results.

Competing interests

The authors declare no competing interests.

Additional information

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