the amount of sunlight hitting our planet at that time was roughly 70% of the amount received today. The new model shares this feature; however, Turbet *et al.* show that if the Sun had been just a little brighter when Earth formed — about 92% of its present luminosity — our planet's steam atmosphere would never have condensed. Instead, Earth would have become similar to Venus, and we would not be around to tell the story.

This finding also has implications for exoplanets — planets around stars other than the Sun. Exoplanets that orbit near the inner edge of the conventional habitable zone, where liquid water can exist on a planet's surface, might not actually be habitable (Fig. 1). Indeed, Turbet and colleagues' theory could be tested by building direct-imaging space telescopes that can observe such planets and take spectra of their atmospheres[10,11].

Another way to test this hypothesis would be to measure the composition of Venus's surface. The planet has highly deformed regions called tesserae that exhibit high infrared emissivity (the effectiveness of emitting energy as thermal radiation). The surface composition of these tesserae is thought to be felsic — that is, the rock is rich in silica and poor in iron — similar to continental rocks on Earth[12]. On our planet, such rocks form by metamorphic processes (in which minerals change form without melting) that occur in the presence of liquid water. If the tesserae turn out instead to be basaltic, like normal sea floor on Earth, liquid water would not have been needed to generate them, further supporting Turbet and colleagues' hypothesis.

The VERITAS mission — part of NASA's Discovery Program — will attempt to analyse the composition of the tesserae and other parts of Venus's surface from orbit using infrared spectroscopy. But definitive measurements might require a lander that can survive the harsh conditions on the surface. This technological challenge is comparable in difficulty to that of imaging exoplanets, and is a worthy goal for future Venus explorations.

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Diet

# Seafood assessed for global human nutrition

**Lotte Lauritzen**

What role might seafood have in boosting human health in diets of the future? A modelling study that assesses how a rise in seafood intake by 2030 might affect human populations worldwide offers a way to begin to answer this. **See p.315**

An adequate and sustainable supply and intake of nutritious food is essential to tackle major global health issues such as dietary deficiencies. Seafood, which in this context includes fish, shellfish and marine mammals, is rich in micronutrients (such as vitamin A, iron, vitamin $B_{12}$ and calcium) needed to combat the most common such deficiencies. Seafood is also the dominant source of marine omega-3 fatty acids, which have many health-promoting effects. On page 315, Golden *et al.*[1] present ambitious research that puts seafood centre stage.

Golden and colleagues' project is part of an initiative that aims to build healthy and sustainable aquatic food systems (see go.nature.com/3tnulm8). The authors carried out modelling analyses to assess the potential benefits on a global scale that increased seafood availability would have on the lowering of micronutrient deficiencies and the boosting of cardiovascular health. They modelled how much seafood production could increase by 2030, using a hypothetical scenario of production reaching the upper limit predicted by the Food and Agriculture Organization of the United Nations (FAO).

The authors' simulation arrived at an 8% gain in seafood supply worldwide by 2030, relative to the simulated production in a status quo scenario extrapolated from current trends. This hypothetical figure might not be particularly interesting in itself, but its value is in providing a good estimate as the basis for the authors' subsequent analyses of health benefits. These analyses are extremely complex, depend on the available data and involve many modelling steps that are based on assumptions that have a potential influence on the results.

It is difficult to get accurate dietary information, even with the typical standard methods used to determine the food intake of individuals, and such methods are not applicable in a worldwide study. So, as with similar global-scale studies, Golden *et al.* used national supply data, and presupposed a close link between food supply and consumption in the national population. The authors estimated the overall food consumption by following models used by the FAO and the Organisation for Economic Co-operation and Development to simulate food supplies on the basis of price and availability. Estimates of dietary intake derived by this method will obviously have limitations in accuracy, and the modelling assumptions might also introduce biases. Moreover, cultural differences between nations would probably affect how a hypothetical increase in seafood production would alter future dietary behaviours in a given national population. Also, people in affluent countries might not necessarily eat more seafood if supply increased, considering that the current intake is low in many countries in which seafood is readily available.

Making assumptions about future patterns of seafood export and import is also tricky. From their modelling results, the authors found that the top three global seafood exporters — Vietnam, China and Norway[2] — would show large increases in their national seafood supply. This is counter-intuitive, because countries that already export most of their production would be expected to expand their export market rather than their national supply if production was upgraded. This is especially so for Norway, which already has one of the highest national seafood intakes in the world[2]. It is therefore necessary to take into account the assumptions made in modelling studies that have multiple layers of analysis, especially universal assumptions in a global

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**Figure 1 | A fish market in the Kemeralti Bazaar, Izmir, Turkey.**

study, because these affect the results of the subsequent analyses.

Once you determine food consumption, it is theoretically simple to estimate nutrient consumption using a database of information about individual foods. However, there can be shortcomings in a database, and this is particularly problematic for seafood because of its high diversity (Fig. 1), only a small percentage of which is usually considered. To address this, Golden *et al.* generated an enormous seafood database, which they used in addition to a large food-composition database, to estimate future global micronutrient and marine omega-3 fatty-acid intake. Gathering the information needed to create a diversified seafood database with complete nutrient-composition data for 2,143 species was a huge task. The authors' validation data indicate that it was worthwhile, and that it provides a valuable upgrade for the field. However, unavoidably, some types of variation in nutrient-intake measures cannot be accounted for – for example, those due to large variations in the content of fat and omega-3 fatty acids in fish depending on the time of year, location and the cut of fish consumed.

Micronutrient deficiencies can be diagnosed by blood-sample analysis, and severe deficiencies can be identified through physical signs. Gathering such deficiency data is obviously impossible for a worldwide population study. Therefore, Golden *et al.* estimated the proportions of national populations having an insufficient micronutrient intake as a way to assess the extent to which the projected rise in global seafood intake could drive reductions in micronutrient deficiencies. However, micronutrient requirements depend on age and sex, and vary between individuals, so the authors modelled how the average per capita nutrient consumptions in each country were distributed according to age and sex. Then, they modelled distribution curves for the micronutrient intake within each age and sex category (for example, women aged 20–30 years old) to estimate the expected number of deficient individuals in each group.

However, the authors had data on intake variations by age and sex from only 13 countries, which they had to use for other countries in the same geographical regions to arrive at benefit estimates. This might have added some uncertainty and biases to the health benefits predicted. Nevertheless, their results indicate that women and children, who are most vulnerable to micronutrient deficiencies, will benefit the most from a rise in seafood consumption.

Overall, Golden and colleagues' results do not indicate any strong correlation between the size of the projected increase in national seafood supply and the estimated benefits in the individual countries. It seems that sub-Saharan Africa and southern parts of Asia, which have the highest global prevalence of micronutrient deficiencies[3], would experience pronounced reductions in, mainly, vitamin $B_{12}$ and zinc deficiencies, even with relatively modest increases in their seafood supply.

The estimated benefits for calcium, on the other hand, coincide largely with the increase in supply. This result is puzzling, because the highest estimated benefits for increased calcium intake occur in countries such as Norway and China, whose populations are currently at low risk of such deficiency[4].

As expected, the authors note some correlation between the estimated increase in seafood supply and the health benefits of marine omega-3 fatty acids for South America, Africa, the Middle East and Europe. However, there were no predicted benefits relating to marine omega-3 fatty acids in their modelled hypothetical scenarios for most of Asia and for the top three seafood exporters, probably because of the high current consumption of seafood in these countries.

The results do not indicate any reductions in vitamin A deficiency in populations with increased seafood supply in their particular country, but instead a general tendency towards adverse effects owing to a lowering of vitamin A intake, especially in Indonesia, Japan, Iran and Norway. The authors suggest that this is due to seafood replacing other vitamin A-rich foods, although fish is one of the best sources of vitamin A, especially oily fish and fish livers. Another point to consider is that the authors base their analysis on the nutritional content of seafood muscle tissue, and do not consider bones, internal organs and adipose tissue, including those currently eaten. Omitting the supply of vitamin A (or other micronutrients) from these tissues runs the risk of underestimating seafood's potential benefits.

Diet is not usually considered to be the main contributor to vitamin D deficiency, which is attributed mainly to inadequate sun exposure at high latitude or to skin being covered[5]. Optimal vitamin D status is, however, achievable through an intake of fatty fish in accordance with recommendations[6]. This indicates that an increase in seafood intake could improve bone health as a consequence of adequate vitamin D intake. Better seafood availability might also aid children's growth, especially in low-income countries where seafood would offer an important supply of high-quality protein.

The estimated benefits of marine omega-3 fatty acids are tied to the authors' chosen cut-off value of 0.4 grams consumed per day, irrespective of sex and age. This value is based on an observed association with a reduction in ischaemic heart disease in adults. However, there is no consensus on the optimal level of intake, and recommendations vary widely from no specific recommended intake to 1 g per day (for people with cardiovascular disease)[7]. The essential role of omega-3 fatty acids began to be recognized in the 1970s and 1980s, and on the basis of accumulating evidence, the total amount and the specific requirements recommended are still being increased. Current evidence indicates that boosting the supply of marine omega-3 fatty acids might have extra benefits, for example to child development or for people with arthritis[8].

Golden and colleagues' work provides a range of methodological advances and some interesting results. Considering the big picture, overall global health would probably improve if seafood availability were to increase, and the authors' models predict that the maximal gains would be in sub-Saharan Africa and southern parts of Asia. The authors' consideration of malnutrition and cardiac diseases associated with diet and other lifestyle factors is a notable approach that is highly relevant for a global-health study. It is a strength of this work that the authors model and assess future changes to the whole diet, instead of just focusing on the effects of an increase in seafood, because their analysis indicates the need to consider potential negative effects of food replacements. This research also provides a proof of concept that such models might be a valuable asset when planning public-health policies — if the models are based on in-depth knowledge about the specific setting in order to make realistic projections.

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Climate science

# The energy costs of climate change

**Katrina Jessoe & Frances C. Moore**

How will global energy usage change as Earth warms? Modelling now suggests that there will be a modest net decrease in energy consumption — but probably at the expense of human well-being in many regions. **See p.308**

Climate change affects many things: the food we grow, human health, the productivity of workers, migration decisions, conflicts and violence, ecosystem services and the amount of energy we consume[1,2]. These disparate and diverse effects are difficult to quantify, particularly in economic terms. Nevertheless, such an evaluation is crucial for analyses of climate and energy policies. US federal agencies, for instance, are required to perform a cost–benefit analysis of all their regulations. For climate and energy policies, this requires them to put a price on carbon dioxide emissions. One measure of this is the social cost of carbon (SCC) — an evaluation of the future costs of emitting one extra tonne of $CO_2$ into the atmosphere, taking into account all the effects of climate change.

Calculating the SCC is a Herculean task. Researchers have used a set of integrated assessment models (IAMs), which pair simple computational models of socio-economic and climate systems. One essential component of IAMs is the damage function, which relates the level of global warming to resulting changes in human welfare. But a considerable problem in all currently used models is that the science supporting damage functions is based on limited data that are decades out of date[3–5]. With the administration of US President Joe Biden now working on a major update to the country's SCC, incorporating better science and economics into the damage functions of IAMs is a high priority[5]. On page 308, Rode *et al.*[6] provide new estimates of how climate change will affect global energy consumption and a price for the portion of the SCC that is attributable to energy expenditure.

The net global effect of future higher temperatures on energy use has been unclear. Higher temperatures are likely to reduce energy demand for heating, but might increase demand for cooling, with the effects differing between regions. The effect of temperature increases on energy consumption will also vary according to people's income. For example, demand for electricity in high-income locations is likely to be more responsive to temperature increases, because people are much more likely to have (or be able to purchase) air conditioners than are people in low-income areas. Projections of the effects of climate change on energy consumption therefore need to take into account geographical differences and income dynamics. Rode and colleagues address both of these dimensions in their study.

The authors combine historical annual income and energy-consumption data from 146 countries with daily temperature and rainfall data at 0.25° × 0.25° resolution, to estimate