Omega-3 nutraceuticals, climate change and threats to the environment: The cases of Antarctic krill and *Calanus finmarchicus*

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Abstract

The nutraceutical market for EPA (eicosapentaenoic acid) and DHA (docosahexaenoic acid) is promoting fishing for *Euphausia superba* (Antarctic krill) in the Southern Ocean and *Calanus finmarchicus* in Norwegian waters. This industry argues that these species are underexploited, but they are essential in their ecosystems, and climate change is altering their geographical distribution. In this perspective, we advocate the cessation of fishing for these species to produce nutraceuticals with EPA and DHA. We argue that this is possible because, contrary to what this industry promotes, the benefits of these fatty acids only seem significant to specific population groups, and not for the general population. Next, we explain that this is desirable because there is evidence that these fisheries may interact with the impact of climate change. Greener sources of EPA and DHA are already available on the market, and their reasonable use would ease pressure on the Arctic and Antarctic ecosystems.

Keywords

Antarctic krill · *Calanus finmarchicus* · Climate change · Docosahexaenoic acid · Eicosapentaenoic acid · Krill oil

INTRODUCTION

The last years have seen an increase in the popularity of fish oil nutraceuticals (Kantor et al. 2016). These oils, rich in the omega-3 fatty acids EPA (eicosapentaenoic acid) and DHA (docosahexaenoic acid), promise to improve cardiovascular health and cognition, as well as protect against diabetes or even cancer (Shahidi and Ambigaipalan 2018). However, voices have been raised denouncing that an increase in the catches of forage fish to supply this growing industry is putting pressure on the already decimated fishing grounds of the planet. Jenkins and colleagues described this threat and put it into the perspective of the studies supporting the health benefits of these oils, and concluded that these fisheries might not be justified (Jenkins et al. 2009). Various companies, in search of alternative sources of EPA and DHA, are now exploiting zooplankton species. They call this practice "fishing down the food web", and justify their activity in the high biomasses of these species in the oceans. Thus, catches of *Euphausia superba* (known as Antarctic krill), once used as food for domestic animals or even as fertiliser (Nicol 2018), are now increasing in the Southern Ocean to prepare these capsules. In addition, a new commercial fishery has recently started in Norwegian waters to capture *Calanus finmarchicus*, a 2–4 mm long calanoid copepod with long antennae and a reddish torpedo-shaped body (Norwegian Directorate of Fisheries 2019).

The companies exploiting Antarctic krill and *C. finmarchicus* claim that these species are underexploited. However, both zooplankton species are essential in their ecosystems, as they occupy the intermediate level in their respective trophic webs, where they link primary producers with predators (Fauichard et al. 2011; Atkinson et al. 2014). Climate change is affecting the stocks and geographic distribution of these zooplankton species (Beaugrand et al. 2003; Flores et al. 2012b; Atkinson et al. 2019), and in the case of Antarctic krill, there is a debate about detrimental effects of the fishery (Krüger et al. 2020; Watters et al. 2020).

In this perspective, we defend that exploiting Antarctic Krill and *C. finmarchicus* to prepare EPA and DHA nutraceuticals is not rational. To do this, we review the current science available on the cardiovascular and
cognitive benefits of these fatty acids, and we conclude that the general population does not benefit from consuming these oils. This, together with the threats posed by these fisheries along with climate change to exploited ecosystems, make us propose the cessation of fishing for these zooplankton species.

HEALTH BENEFITS OF EPA AND DHA

Based on the best available evidence, there are not significant cardiovascular benefits of EPA and DHA in the broad population

EPA and DHA are long-chain (≥ C₂₀) polyunsaturated fatty acids (LC-PUFA) of the omega-3 family. Humans obtain these fatty acids ingesting fish and seafood, but we are also genetically equipped to produce these fatty acids from dietary ω-3-linolenic acid (ALA, Fig. 1) (Bradbury 2011). Interest on the benefits of EPA and DHA on human health began when Danish researchers Bang and Dyerberg associated the low incidence of ischemic heart disease in the Inuit people of Greenland to their diet of fish, whales and seals, rich in these fatty acids (Dyerberg et al. 1975; Bang et al. 1976).

This work and the epidemiological studies that followed suggested that EPA and DHA prevent cardiovascular risk (Simopoulos 2002). Despite the importance of these works, we must emphasize that by their nature, these studies are only designed to generate work hypotheses, and not to confirm them (Greenberg 2018). Subsequent randomised placebo-controlled trials (RPCTs), whose design allows questioning the working hypothesis, are yielding, nevertheless, contradictory results. On the one hand, supplementation with EPA and DHA reduced the risk of sudden cardiac death (GISSI-Prevenzione Investigators 1999), slightly reduced death rate and admission to hospital for cardiovascular reasons (Tavazzi et al. 2008), prevented non-fatal coronary events in hypercholesterolaemic subjects (Yokoyama et al. 2007), and lowered the risk of cardiovascular death in subjects with elevated triglyceride levels, but in this case, using only high doses of EPA-ethyl ester (Bhatt et al. 2018). On the other hand, other RPCTs reported that supplementation did not reduce the rate of

Fig. 1 Biosynthesis pathway of EPA (eicosapentaenoic acid) and DHA (docosahexaenoic acid) in the liver. The pathway starts with the essential fatty acid ALA (ω-3-linolenic acid), which must be obtained from the diet. This fatty acid undergoes a series of desaturations performed by Δ5-desaturase and Δ6-desaturase (FADS2 and FADS1 genes, respectively), and also elongations, performed by elongase-5 (ELOVL5 gene) to yield EPA. Then, EPA is elongated by elongase-5 to yield DPA. From DPA, DHA can be produced either by elongation (elongase-2, ELOVL2 gene), desaturation (Δ6-desaturase) and β-oxidation in the peroxisome, or by direct desaturation by Δ6-desaturase (Park et al. 2015). Apart from DHA, EPA and DPA (docosapentaenoic acid) are found in appreciable amounts in human plasma. The alpha (α) end of the fatty acids denotes the carbon counting start from the carboxy end and coincides with the recognition site of the desaturase enzymes, whose number specifies the carbon where the desaturation is performed. The omega end denotes the end of the molecule opposite to the carboxy group and is used to denote the position of the desaturations in the molecule. SDA stearidonic acid, ETA eicosatetraenoic acid, TPA tetracosapentaenoic acid; THA, tetracosahexaenoic acid

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cardiovascular events in subjects at high risk of cardio-
vascular events (Bosch et al. 2012), did not lower cardio-
vacular mortality and morbidity on subjects with multiple
vascular risk factors (Roncaglioni et al. 2013), did not
decrease the risk of serious cardiovascular events in
patients with diabetes and without cardiovascular disease
(Bowman et al. 2018) and did not reduce the incidence of
major cardiovascular events in patients free of cardiovas-
cular disease (Manson et al. 2019). EPA and DHA industry
representatives are concerned about these inconsistencies.
Among the possible causes, they point to the use of inade-
quate statistics, or the general lack of measurement of the
levels of EPA and DHA in the participants of the trials, as
the researchers do not know the baseline status for these
fatty acids or the effectiveness of the formulations in the
participants (Rice et al. 2016; Serini and Calviello 2020).

Despite this mix of positive and non-significant results,
EFSA recommends the consumption of between 100 and
450 mg of EPA and DHA daily for children, adults and
pregnant women (EFSA Panel on Dietetic Products 2010)
and allows companies to claim in their products that EPA
and DHA contribute to the normal function of the heart
(EFSA Panel on Dietetic Products and Allergies 2010b,
2011). FDA, on the other hand, while also allows for health
claims, enforces discretion requesting the addition of the
statement: “However, FDA has concluded that the evi-
dence is inconsistent and inconclusive” (Center for Food
Safety and Applied Nutrition (CFSAN) 2014).

To date, meta-analyses on available RPCTs with EPA-
and DHA-rich oils or foods, conducted by independent
groups, in different years and with different methodologies,
coincide in that EPA and DHA supplementation does not
prevent cardiovascular disease (Rizos et al. 2012; Aung
et al. 2018; Abdelhamid et al. 2020) (Table 1). The most
recent of these meta-analyses included 86 RPCTs with
adults at different cardiovascular risks, and concluded that
EPA and DHA supplementation did not significantly lower
all-cause mortality, cardiovascular mortality, cardiovas-
cular events, stroke or arrhythmia in adults at cardiovascular
risk (Abdelhamid et al. 2020). Nevertheless, these authors
found low-certainty evidence that supplementation slightly
reduced events and mortality from coronary heart disease.
These reductions, measured as number needed to treat for
an additional beneficial outcome (NNTB) were, however,
very small. As an example, these authors estimated that
334 people would need to take EPA and DHA supplements
for four years for one person to avoid death from coronary
heart disease; the other 333 people would not get any
benefit. Given these results, Abdelhamid and colleagues
suggest that EPA and DHA supplementation “is probably
not useful for preventing or treating cardiovascular dis-
ease”. For krill oil, the only meta-analysis of RPCTs per-
formed to date showed similar results to fish oil (Ursoniu
et al. 2017). Regarding Calanus oil, the antioxidant, anti-
cholesterolemic and anti-inflammatory roles reported for
this oil at the preclinical level (Gasmi et al. 2020) have
only been recently tested in humans (Wasserfurth et al.
2020). In this study, the consumption of Calanus oil in
people who were exercising moderately contributed to
losing weight in a similar way as eating a healthy diet.

Importantly, to give full meaning and credibility to the
health benefits of a nutrient, it is necessary to describe
the molecular mechanisms that underlie the effects found in
the clinic. To date, a large number of molecular mecha-
nisms by which EPA and DHA are involved in human
physiology have been described. Both fatty acids bind to
the GPR120 receptor to promote healthy adipogenesis,
maintain insulin sensitisation and control inflammation (Oh
et al. 2010; Hilgendorf et al. 2019). EPA and DHA also
undergo enzymatic modifications to yield signals such as
protectins, resolvins and maresins (Fig. 2) (Watson et al.
2019), which promote resolution of inflammation and
modulate the immune response (Spite et al. 2014; Serhan
and Levy 2018). EPA and DHA are also precursors of
omega-3 endocannabinoids (Fig. 2), which again regulate
inflammation (McDougall et al. 2017) but are also involved
in cognition, pain and cancer (Watson et al. 2019). Many of
these functions of EPA- and DHA-derived molecules have
been proposed to mediate the claimed benefits of supple-
mentation. For example, EPA and DHA have been prop-
osed to regulate atherosclerosis (Zehr and Walker 2018),
hypertriglyceridemia (Arca et al. 2018), platelet function
(Lagarde et al. 2018) and blood pressure (Guo et al. 2019).
Of note, some of these EPA- and DHA-derived molecules
are even used as a model to synthesize analogues with
potentially greater beneficial effects (Imig et al. 2010).
Nevertheless, only clear and consistently positive results
from human trials, comparable to those published with cell
cultures and animal models, can support the use of EPA
and DHA to improve cardiovascular health (Mason et al.
2020).

EPA and DHA supplementation seem to benefit
vision and cognition, but in specific cases

EPA and DHA are also claimed as nutrients with beneficial
effects in vision and cognition, and much attention is
currently being paid to the potential role of these molecules
in neurodegenerative disorders, both at the preclinical and
at the clinical level (Martins et al. 2020; Yde Ohki et al.
2020). DHA is present in approximately 50% of the
phospholipids forming the membranes of the rod photore-
ceptors in the retina (Shindou et al. 2017), and constitutes
about 18% of the total fatty acids present in the grey matter
of the brain (Skinner et al. 1993). The importance of DHA
in vision and cognition is in great part because DHA-
phospholipids enhance the flexibility of specialized cell membranes in these organs and facilitate the function of embedded proteins. This is because DHA is almost entirely populated with double bonds (Fig. 1), which give the entire molecule an unusually high degree of torsional rotation (Gawrisch et al. 2003) that translates in great flexibility in all three axes of space (Barelli and Antonny 2016). Thus, in staked discs of rod photoreceptors, which are composed of highly bent membranes (Burgoyne et al. 2015), DHA-phospholipids facilitate continuous and efficient disc formation and recycling (Shindou et al. 2017). At the same time, in these membranes, DHA-phospholipids assist rhodopsin in its transition from the inactive to the active state when it receives a light photon (Salas-Estrada et al. 2018).

In the membrane of neuronal axons (Yang et al. 2012), DHA-phospholipids facilitate the formation of vesicles with neurotransmitters, essential for synaptic transduction (Manni et al. 2018). In addition to these structural roles, DHA, together with EPA, is a precursor in brain and retina of yet another family of signalling molecules, the eloovanoids (Fig. 2), which are elongated and hydroxylated derivatives of these fatty acids (Shindou et al. 2017). Elovanoids promote cellular pathways to counteract uncompensated stresses in these organs (Shindou et al. 2017; Do et al. 2019).

These molecular roles of EPA and DHA in vision and cognition suggest clinical benefits for supplementation, at least in certain conditions. Thus, in preterm infants, a meta-analysis suggested that supplementation is beneficial in terms of visual acuity and cognitive development (Shulkin et al. 2018), likely because dietary EPA and DHA compensated the lack of placental transfer of these fatty acids due to premature birth (Larqué et al. 2011). At the perinatal stage, when the formation of neural circuits is intense, EPA and DHA are likely crucial. As an example, optimal levels of EPA and DHA are essential for the appropriate development of the neural networks that support the reward system in rats (Ducrocq et al. 2020).

### Table 1

| Meta-analysis | Health field | RPCTs analysed | Author’s conclusions |
|---------------|--------------|----------------|----------------------|
| Rizos et al. (2012) | Cardiovascular Health | 20 | Omega-3 PUFA supplementation was not associated with a lower risk of all-cause mortality, cardiac death, sudden death, myocardial infarction, or stroke based on relative and absolute measures of association |
| Aung et al. (2018) | Cardiovascular Health | 10 | Omega-3 fatty acids had no significant association with fatal or nonfatal coronary heart disease or any major vascular events. It provides no support for current recommendations for the use of such supplements in people with a history of coronary heart disease |
| Abdelhamid et al. (2020) | Cardiovascular Health | 86 | Moderate- and low-certainty evidence suggests that increasing LCn3 slightly reduces risk of coronary heart disease mortality and events, and reduces serum triglycerides (evidence mainly from supplement trials) |
| Brainard et al. (2020) | Cognition in healthy adults | 38 | Long-chain omega-3 probably has little or no effect on new neurocognitive outcomes or cognitive impairment |
| Shulkin et al. (2018) | Childhood psychomotor and visual development | 38 | n-3 PUFA supplementation improves childhood psychomotor and visual development |
| Chang et al. (2018) | ADHD | 7 | We provide strong evidence supporting a role for n3-PUFAs deficiency in ADHD, and for advocating n-3 PUFAs supplementation as a clinically relevant intervention in this group, especially if guided by a biomarker-based personalisation approach |
| Liao et al. (2019) | Depression | 26 | Current evidence supports the finding that omega-3 PUFAs with EPA ≥ 60% at a dosage of ≤ 1 g/d would have beneficial effects on depression. We note that the long-term efficacy and health effects of omega-3 PUFA supplementation in depression have yet to be elucidated |
| Deane et al. (2019) | Depression and anxiety | 31 | Long-chain omega-3 supplementation probably has little or no effect in preventing depression or anxiety symptoms |
| Canhada et al. (2018) | Alzheimer’s disease | 7 | The effects of omega-3 fatty acids supplementation in mild AD corroborate epidemiologic/observational studies showing that omega-3 fatty acids may be beneficial in disease onset, when there is slight impairment of brain function |
| Burckhardt et al. (2016) | Dementia | 3 | We found no convincing evidence for the efficacy of omega-3 PUFA supplements in the treatment of mild to moderate AD |
these low levels of EPA and DHA do not appear to be related to diet (Noaghiul and Hibbeln 2003; Peet 2004).

Children and adolescents with attention deficit hyperactivity disorder (ADHD) significantly improved their clinical symptoms and cognitive performance (Chang et al. 2018), especially individuals with low basal levels of these fatty acids (Chang et al. 2019). Beneficial effects in depression is disputed (Deane et al. 2019; Liao et al. 2019). Alzheimer’s patients, who usually have low levels of DHA in the brain (de Wilde et al. 2017) due to a decrease of DHA synthesis in the liver (Astarita et al. 2010), an impairment of DHA import to the brain (Ochiai et al. 2019) and poor eating habits (Samadi et al. 2019), could benefit at the early stage of the disease (Canhada et al. 2018). It is therefore tempting to hypothesise that these mental disorders may have a genetic component responsible of a reduced synthesis of EPA and/or DHA, which are essential for the successful development, maintenance and function of neural networks.

Nevertheless, a recent meta-analysis of 38 RPCTs concluded that supplementation does not seem to help healthy adults, as it does not prevent the onset of neurocognitive illness (Brainard et al. 2020). Despite this, EFSA allows the industry to claim that supplementation with EPA and DHA contributes to the maintenance of normal visual and cognitive functions (EFSA Panel on Dietetic Products and Allergies 2010a, 2011). Here, although the molecular roles of EPA and DHA and clinical data agree in specific situations or conditions, such as premature babies, adolescents with ADHD and Alzheimer’s patients, there is no clinical support for supplementation for the general population. For this reason, we believe that the health claims that EFSA allows in terms of vision and cognition, extended to the entire population, exceed the real need.

**Evidence suggest that DHA synthesis in healthy adults from ALA is sufficient to supply the brain**

Scientific literature generally agrees that DHA synthesis in humans occurs with very low efficiency (Fig. 1). On average, the male appears to convert only 1% of ingested ALA to DHA in the liver (Goyens et al. 2006; Lin et al. 2010) and female 8% (Burdge and Wootton 2002). Companies that market EPA and DHA oils use this reported inefficiency in their marketing efforts, as it undoubtedly favours their business interests. Nevertheless, authors like Domenichiello and colleagues have elegantly argued that DHA synthesis in humans may be sufficient to maintain brain function (Domenichiello et al. 2015).

In this line, recent research suggests that prior evaluation of DHA synthesis in humans yielded equivocal results. Pignitter et al. have used circulating LDL (low-density lipoprotein) as a proxy to assess DHA synthesis in the liver, unlike previous studies, which looked for DHA in the fraction of circulating phospholipids, fatty acids or red blood cells. As a result, Pignitter et al. reported that in their experiment, 30% of ingested ALA was converted to DHA (Pignitter et al. 2018).

In addition to this, many studies have reported that the retina and brain bear cell types that synthesize DHA. Examples of this in the retina are the retinal pigment epithelium (Wang and Anderson 1993; Chen et al. 1999), microvascular endothelial cells (Delton-Vandenbroucke et al. 1997) and retinal neurons (Simón et al. 2016). In the

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**Fig. 2** Signalling molecules derived from EPA and DHA. In black is depicted the structure of EPA and DHA. In blue are highlighted the enzymatically made additions yielding resolvins, protectins, maresins, endocannabinoids and elovanoids. *EPA* eicosapentaenoic acid, *DHA* docosahexaenoic acid, RvE1 Resolvin-EPA 1, RvD1 Resolvin-DHA 1, PD1 Protectin-DHA X, MaR1 Maresin 1, MaR2 Maresin 2, 1-EPG 1-eicosapentaenoyle-glycerol, 1-DHG 1-docosahexaenoyle-glycerol, EPA-DA EPA-Dopamine, DHA-DA DHA-Dopamine, EPA-5HT EPA-Serotonin, DHA-5HT DHA-Serotonin, ELV-N32 Elovanoid N32, ELV-34 Elovanoid N34
brain, astrocytes (Moore et al. 1991; Williard et al. 2001), microvascular cells (Delton-Vandenbroucke et al. 1997) and some types of neurons (Kaduce et al. 2008) also produce DHA. A proper assessment of the magnitude of this DHA synthesized and used in the retina and brain could contribute to demystifying the low production capacity of DHA in humans.

Evolution also indicates that the synthesis of DHA in humans is a physiologically relevant process. The FADS1 and FADS2 genes are responsible for encoding the Δ-desaturases that constitute the bottlenecks that determine the synthesis rate of this fatty acid (Fig. 1). After 23 000 years of a diet of fish, seals and whales, the Inuit of Greenland have fixed less efficient alleles of FADS1 and FADS2 to produce less EPA and DHA and conserve ALA, scarce in their diet (Fumagalli et al. 2015). On the other hand, the predominantly vegetarian diet of Europeans during the Bronze Age caused them to fix more active alleles of FADS1 and FADS2 to produce more EPA and DHA (Buckley et al. 2017). The notion that the diet is capable of modulating the genetics of DHA synthesis throughout evolution suggests that this process is key in human physiology.

According to the above, despite the influence of diet on the levels of DHA in the blood [up to 40% less in vegans and vegetarians (Domenichiello et al. 2015)], there are factors such as gender, stage of life, genetic background and state of health that may have a determining role on internal levels of this fatty acid. For this reason, we believe that supplementation with EPA and DHA should be recommended only after a personalized analysis, and the EPA and DHA nutraceutical industry should not target healthy adults in their marketing efforts.

ANTARCTIC KRILL AND C. FINMARCHICUS FISHERIES. MANAGEMENT, THREATS TO THE ECOSYSTEM AND CLIMATE CHANGE

Although supplementation with EPA and DHA seems unnecessary for healthy adults, we believe that this argument may be insufficient to stir consciences and reduce the exploitation of ecosystems to source these fatty acids. That is why we describe below how Antarctic krill and Calanus fisheries can add up to climate change and threaten unique ecosystems.

E. superba and C. finmarchicus, ecological importance and commercial interest

Antarctic krill, a crustacean often compared to shrimp and about 6 cm long, inhabits all waters surrounding Antarctica (Fig. 3), occupying the key intermediate trophic level of this ecosystem (Flores et al. 2012a). Here, this crustacean grazes phytoplankton and serves as feed for whales, penguins, seals, fish and birds (Murphy et al. 2007). Exploratory Antarctic fishing began in the early 1960s by the former Soviet Union, driven by declining high seas fish stocks and restricted access to the waters of coastal states (Hofman 2017). In 1977, R. M. Laws formulated what later became known as the ‘krill surplus’ hypothesis, according to which the observed increase in seal and penguin populations in those years was due to the previous near-extinction of the whales, which led to greater availability of krill for other species (Laws et al. 1977). At that time, this hypothesis was used by others to justify krill fisheries, since it was suggested that this ‘krill surplus’ could be destined for human use (Hofman 2017). Nevertheless, this hypothesis has been reviewed and considered incomplete (Surma et al. 2014). After capturing more than 400 000 tonnes of Antarctic krill per season in the 1980s and using it to feed pigs and chickens, to prepare food for humans or used as fertilizer (Nicol 2018), CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources) entered into force to regulate this practice (CCAMLR 1980).

C. finmarchicus thrives in the subpolar waters of the North Atlantic Ocean (Scott et al. 2000), and is dominant in the Norwegian Sea (Choquet et al. 2017; Strand et al. 2020) (Fig. 5a). Likewise Antarctic krill, C. finmarchicus occupies the key intermediate level in its trophic web (Faucald et al. 2011), grazing phytoplankton and serving as prey to the North Atlantic right whale (Cronin et al. 2017), and to fish species such as cod (in the larval stage) (Ottersen et al. 2014), herring (Prokopchuk 2009) and capelin (Buren et al. 2014). After small trials with this copepod for aquaculture, pet food and even as an ingredient for soups in the 1960s (Wiborg 1976), the company Calanus AS (Tromsø, Norway) started to fish this copepod experimentally in 2003 (Fiskeridirektoratet 2016). In 2016, the Norwegian Ministry of Climate and Environment (NMCE) regulated the commercial fishing of this copepod, and in 2019, this regulation entered into force (Nærings- og fiskeridepartementet 2019).

Management rules of these fisheries

To protect Antarctic krill and its predators from the impact of the fishery, CCAMLR supervised an international effort to estimate krill biomass in the Atlantic sector of the Southern Ocean (Trathan et al. 1995), where 58–71% of total krill biomass exists (Atkinson et al. 2008), and the fishery was concentrating. CCALMR used this data together with the annual growth rate, mortality rate, and recruitment variability to calculate a precautionary fishing quota of 5.61 million tonnes per season, (9.23% of the
estimated 60.3 million tonnes of krill biomass) (Butterworth et al. 1992; Constable et al. 2000; SC-CAMLR 2010). CCAMLR also established a lower quota known as trigger level to mark the use of more restrictive fishing rules under small-scale management units (SSMUs). The trigger level was established as the equivalent of the maximum annual catches in the 1980s, which were considered safe for the ecosystem at that time (SC-CAMLR 1991; Hill et al. 2016). This trigger level, set at 620 000 tonnes per season (roughly 1% of basal biomass), was divided among subareas 48.1–4 (Fig. 3) (CCAMLR 2016a). Once this volume of catches was reached in any of the subareas, the use of the SSMUs would begin. However, CCAMLR has not yet agreed on regulations for working with SSMUs (Nicol and Foster 2016), thus making the trigger level the interim catch limit.

It has been suggested that the trigger level is not safe for the Antarctic ecosystem (Medley et al. 2009). This level has been reached in the last seven seasons in subarea 48.1, and captures are rapidly increasing in subarea 48.2 (Fig. 4a), driven by an increase in the activity of Norwegian companies (Fig. 4b) (CCAMLR 2019). Furthermore, fishing hotspots have been identified in subarea 48.1 (Fig. 3b) (Santa Cruz et al. 2018), which coincide with the feeding grounds of whales (Herr et al. 2016), penguins and Antarctic fur seals inhabiting this region (Miller et al. 2010; Hinke et al. 2017). A recent work by Watters and colleagues confirms the detrimental effect of these overlaps, finding a significant correlation of periods of penguin underperformance with years of high krill catches in their fishing grounds (Watters et al. 2020). Therefore, measures like the implementation of SSMU rules are urgent, but CCAMLR suffers a continuous internal struggle between the fishing and conservative interests of the countries that comprise this organisation (Jacquet et al. 2016; Hofman 2019). Other examples of this are the difficulties to establish marine protected areas (MPAs) (Brooks 2013; Brooks et al. 2020) or to address the impact of the fishery (Constable et al. 2000). Because of this, and because they are aware of the potential impact of their activities, fishing companies sometimes make unilateral decisions and, for example, temporarily suspend fishing near penguin colonies, even when CCAMLR has not reached an agreement to implement this measure (CCAMLR 2016b). Nevertheless, other movements of these companies are criticised, like the process of obtaining of Certification as a Sustainable Fishery from the Marine Stewardship Council (MSC) by Aker BioMarine AS (Medley et al. 2009; Christian et al. 2013).

Despite the difficulties that CCAMLR faces in managing Antarctic krill fishery, the Norwegian Ministry of Climate and Environment (NMCE) has been inspired by the
work of this organisation to establish a fishing quota for *C. finmarchicus*. Of note, although NMCE recognised the need for a research effort similar to that supervised by CCAMLR, this agency realised that obtaining this empirical data would require a long-term international initiative that was difficult to take on (Fiskeridirektoratet 2016). Of note, in 2012 the Norwegian Ministry of Fisheries and Coastal Affairs requested to the International Council for the Exploration of the Sea (ICES) an “exploratory assessment of *Calanus finmarchicus* in the Norwegian Sea”. However, this proposal was not supported financially, and ICES could only limit itself to commenting on the data generated by the Norwegian government. In its report, ICES noted that the estimated annual consumption of *C. finmarchicus* by pelagic and mesopelagic fish, as well as by invertebrates, left little (or no) biomass available for a fishery. In another comment, ICES focused on by-catch concerns, as this fishery uses 500-micron mesh nets that can collect fish eggs and larvae. Thus, in an experiment that caught 85 075 kg of *C. finmarchicus*, thousands of fish eggs and larvae were accidentally captured. In the worst-case scenario calculations, ICES estimated that this by-catch eliminated the possibility of recruitment of 41 724 cod, which is equivalent to 327 370 kg of fish. This is almost four times more biomass than that of captured *C. finmarchicus*. However, and as the authors ironically point out in their report, the value of Calanus oil is higher than that of cod (ICES 2017). The Norwegian government, for its part, considers this by-catch to be negligible, but encourages fishing to be limited to areas with low presence of fish eggs and larvae (Fiskeridirektoratet 2016).

NMCE estimated the basal biomass of *C. finmarchicus* in Norwegian waters at 33 million tonnes, and applied the precautionary fishing quota that CCAMLR calculated for Antarctic krill (9.23%, rounded to 10% of basal biomass) (Fiskeridirektoratet 2016). This yielded a precautionary catch limit of 3.3 million tonnes per season. As NMCE considered that there is uncertainty about the estimation of *C. finmarchicus* basal biomass, the resilience of this copepod and that of its predators against fishing, the effects of the accidental capture of fish eggs and the impact of climate change, this organism decided to adopt a more restrictive fishing quota. Again, NMCE, inspired by the work of CCAMLR, adopted their trigger level (1% of basal biomass) for *C. finmarchicus*. This yielded a catch limit of 330 000 tonnes per season (Nærings- og fiskeridepartementet 2019). Until 2018, the catches of *C. finmarchicus* have been less than 1% of the trigger level (Fig. 5b). Therefore, at the current stage of development, this fishery is unlikely to have impacted the population of *C. finmarchicus* or its predators. However, the collateral capture of fish eggs and larvae in fishing nets is a cause of concern for the authorities and for the companies that fish for this crustacean. If this problem is not resolved, increased fishing efforts can affect the fish populations that inhabit the *C. finmarchicus* fishing area and, by extension, the species that feed on them (Eysteinsson et al. 2018). It is therefore surprising that NMCE uses CCAMLR rules for Calanus fishery when these rules are being questioned, and furthermore *C. finmarchicus* is a different species, lives in different waters and is part of a different trophic web.

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**Fig. 4** Catches of Antarctic krill. **a** Catches per season in statistical subareas 48.1, 48.2 and 48.3, represented as the percentage of the trigger level. Data obtained from the Fishery Report: *Euphausia superba* in Area 48 (CCAMLR Secretariat 2020). Each fishing season is represented by the year it ends. **b** Total seasonal catches per country. Data obtained from CCAMLR Statistical Bulletin (2019, Volume 31, Table 8.1—Catch Effort Data)
The impact of climate change and interactions with the fisheries

We have described above the weaknesses in the regulations that govern Antarctic krill and Calanus fisheries. Now we describe how climate change affects the exploited ecosystems and how the fisheries may aggravate this impact.

The area of Antarctic Peninsula is considered a climatological anomaly within Antarctica (Vaughan et al. 2003) since it is experiencing higher increases in surface air temperature than the rest of the continent (2–5 °C in the last 50 years) (Vaughan et al. 2001; Compo et al. 2011; González and Fortuny 2018). Water temperature increases in this area are also higher than average, due to a change in the wind regime that is causing a greater entry of deep circumpolar warm water in the Amundsen Sea (Cook et al. 2016; Holland et al. 2019). Thus, the increase in air and water temperatures are making the sea ice extent 7% lower (Comiso et al. 2011; Parkinson 2019) and last three days less each year (Stammerjohn et al. 2012). Glaciers are retreating (Cook et al. 2016), and ice shelves are melting (Étienne et al. 2019; Rignot et al. 2019), which is promoting a decrease in the ice sheet of the Antarctic Peninsula (Shepherd et al. 2018; Rignot et al. 2019). Sea ice is a crucial habitat for the diatoms that constitute the main feed for the post-larval stage of krill (Montes-Hugo et al. 2009; Flores et al. 2012b). Although there is a debate about whether sea ice decline, water temperature increase and water acidification is affecting krill biomass (Atkinson et al. 2004; Melbourne-Thomas et al. 2016; Cox et al. 2018; Hill et al. 2019), a majority of researchers defend that climate change is threatening Antarctic krill (Saba et al. 2012; Kawaguchi et al. 2013; Piñones and Fedorov 2016), to a point that has forced a southward migration of this crustacean looking for colder waters (Atkinson et al. 2019).

Importantly, climate change and the fishery seem to be interacting to cause a decrease of penguins in the Antarctic Peninsula (Trivelpiece et al. 2011; Klein et al. 2018; Krüger et al. 2020) and produce stress in pack-ice seals (Forcada et al. 2012). Despite this, the moratorium on commercial whaling implemented in the mid-1980s is allowing the whales to recoup, with humpback whales (Megaptera novaeangliae) likely recovering their pre-exploitation levels by 2030 (Zerbini et al. 2019). Nevertheless, a rough estimate from these authors suggests that only humpback whales are currently removing 2.5–4.3% of Antarctic krill biomass per season in the South Atlantic. For its part, CCAMLR allows for captures up to 1% of Antarctic krill biomass in this sector of the Southern Ocean. If we also take into account the biomass of krill consumed by penguins, seals and birds, and the confluence of these species with the fishery in the same fishing grounds (Santa Cruz et al. 2018) there is a significant potential for a remodelling of the structure of this ecosystem (Zerbini et al. 2019). Furthermore, a more fierce fight for available krill, together with the expected decrease in biomass of this crustacean in the future due to climate change, has led different authors to predict that whale populations will decline again in the coming decades (Wiedenmann et al. 2011; Seyboth et al. 2016; Tulloch et al. 2019).

Sea surface temperature is also increasing in the North Atlantic Ocean (Abram et al. 2016), and C. finmarchicus...
does not seem able to adapt to this change (Hinder et al. 2014). As a consequence, the temperate species C. helgolandicus is replacing C. finmarchicus at the south of the Norwegian Sea (Montero et al. 2020), and this species is also decreasing in the south-western Norwegian Sea (Kristiansen et al. 2019). Ultimately, and similarly to Antarctic krill in the south, the distribution area of C. finmarchicus is shifting north (Beaugrand et al. 2002; Chust et al. 2013; Montero et al. 2020). The weakening of the Atlantic Southern Overflowing Circulation (AMOC), also caused by global warming (Rahmstorf et al. 2015; Caesar et al. 2018; Thornalley et al. 2018) could result in less mobilisation of nutrients to the photic layer, which would negatively affect the microalgal blooms that C. finmarchicus feeds on (Osman et al. 2019). Decreases in the biomass of phytoplankton and changes in the timing of their blooms can, in turn, have a substantial impact on the blooms of C. finmarchicus. The specific lipid profile and lipid load of this species, as well as its size, are more advantageous for cod larvae than those of C. helgolandicus, the species that is replacing C. finmarchicus in these waters. These changes in the composition of the prey of cod larvae can result in a decrease in the survival and recruitment of this fish (Kattner and Hagen 2009; Kristiansen et al. 2011). Projections of a continuous scenario of high greenhouse gas emissions (temperature increase of about 4.3 °C by 2100, relative to pre-industrial temperatures) (IPCC 2013), predict that the biomass of C. finmarchicus may decrease up to 50% in the southern limits of its distribution at the end of this century (Grieve et al. 2017). These threats are expected to have cascade impacts on fish and the threatened North Atlantic right whale.

These whales, which mainly feed on this copepod (Baumgartner and Mate 2003; Pendleton et al. 2012), and of which only 409 individuals remain in the world (Pettis et al. 2019), may be irretrievably affected by these changes in prey availability (Meyer-Guthrold and Greene 2018). Birds such as the common guillemot (Uria aalge) or the Atlantic puffin (Fratercula arctica), whose diet is based on fish that feed on C. finmarchicus, will entrust their survival to their adaptability to move northwards in search of prey (Frederiksen et al. 2013). Little auk (Alle alle), which feeds directly on C. glacialis, a more nutritious species than C. finmarchicus (Kidawa et al. 2014), could also be affected if this species is replaced by C. finmarchicus in northern waters (Karnovsky et al. 2010; Amélineau et al. 2019). These changes in the distribution and biomass of C. finmarchicus are also detrimental to its role in the sequestration of atmospheric carbon (Brun et al. 2019). Through its faecal pellets and discarded carapaces, as well as by the catabolism in the depths of the ocean of the fatty acids that they synthesise in the photic layer in spring, C. finmarchicus contributes to the role that the ocean plays in the control of atmospheric CO2 (Jónasdóttir et al. 2015).

CONCLUDING REMARKS

We tend to trust the publicity displayed by the companies commercialising nutritional supplements, either because we are not trained to challenge it, or we do not have time to evaluate all the points of view on their effectiveness. Besides, the possibility of consuming these products allows us a certain degree of self-indulgence with our lifestyle. Nevertheless, the best science available today suggests that supplements with EPA and DHA have no benefit in vascular or cognitive health for healthy adults. The best available science also conclude that climate change is affecting our planet, especially the poles and their ecosystems. Therefore, we encourage counteracting our comfortable position adopting a varied and healthy diet, practicing moderate exercise, and thinking that extracting EPA and DHA from our ecosystems threatens the equilibrium of the planet where we live.

For population groups that could benefit from supplementation, such as premature babies, children at risk for mental illness in adulthood due to genetically low levels of EPA and DHA, and for patients with Alzheimer’s disease, we advocate for supplementation with EPA and DHA only by informed recommendation, and using non-extractive or recycled sources, such as the cultivation of heterotrophic microalgae or fish trimming.

We suggest EFSA and FDA re-evaluate the latest published meta-analyses to reconsider the health claims they allow. An eventual decrease in the importance of these health claims, together with truthful information about the threats that these fisheries and climate change pose, could push CCAMLR and the Norwegian government to apply the precautionary principle and work towards a gradual cessation of these fisheries. Importantly, we extend this request to forage fish fisheries, as these species, like Antarctic krill and C. finmarchicus, also occupy the key intermediate level in their trophic webs.

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