Will the Oceans Help Feed Humanity?

CARLOS M. DUARTE, MARIANNE HOLMER, YNGVAR OLSEN, DORIS SOTO, NÚRIA MARBÀ, JOANA GUIU, KENNY BLACK, AND IOANNIS KARAKASSIS

Constraints on the availability of freshwater and land plants and animals to feed the 9.2 billion humans projected to inhabit Earth by 2050 can be overcome by enhancing the contribution the ocean makes to food production. Catches from ocean fisheries are unlikely to recover without adequate conservation measures, so the greater contribution of the oceans to feeding humanity must be derived largely from mariculture. For the effort to be successful, mariculture must close the production cycle to abandon its current dependence on fisheries catches; enhance the production of edible macroalgae and filter-feeder organisms; minimize environmental impacts; and increase integration with food production on land, transferring water-intensive components of the human diet (i.e., production of animal protein) to the ocean. Accommodating these changes will enable the oceans to become a major source of food, which we believe will constitute the next food revolution in human history.

Keywords: aquiculture, food, animals, plants, bottlenecks

The human population is projected to reach 9200 million by 2050 (UN 2007), which is within estimates of the maximum carrying capacity of the planet (Cohen 1995). A fundamental question for science is whether it is possible to increase food production to meet the demands of a human population of that magnitude.

There is little room for optimism. Available water resources appear insufficient for agriculture to meet the food demands of 9200 million people (Cohen 1995, CAWMA 2007). The present population already experiences water stress (CAWMA 2007), which is exacerbated by the interactive effects of population growth and climate change (Vörösmarty et al. 2000). In addition, global fisheries landings have been declining since the mid-1980s (Pauly et al. 2003), contributing to the current food production crisis. Under this scenario, marine aquaculture (hereafter mariculture), the food-producing sector least dependent on freshwater availability (Verdegem et al. 2006), will be enlisted to help feed humanity in the 21st century (Marra 2005). Global terrestrial production and marine primary production are comparable in magnitude (Field et al. 1998), but marine food now contributes only 2% to the human food supply (FAO 2006a), as the development of controlled food production in the ocean lags several millennia behind that on land (Duarte et al. 2007). Aquaculture production currently faces important challenges (Diana 2009) that may hinder its future development. Because large-scale domestication of the ocean should be a mainstay of the response to future food crises (Marra 2005), it is imperative to determine what is required to bring about this domestication. Here we build on recent analyses (Diana 2009) to examine the prospects for mariculture becoming a major force to meet growing human food demands, and we analyze the bottlenecks and challenges mariculture must overcome.

Ceilings to agricultural food production

Food sufficiency requires some 900 cubic meters (m^3) of water per person per year (Falkenmark 1997), and about 9000 to 14,000 km^3 per year are available for human use (Cohen 1995). Thus, a maximum of 10,000 million to 15,500 million people can be supported. Indeed, estimates of the maximum human population that Earth can sustain range from 6000 million to 15,000 million, with a median of about 10,000 million people (Cohen 1995). Far fewer people can be supported if less water is available for agriculture and nutrient requirements—particularly the fraction met by meat intake—increase.

Indeed, the percentage of total water use co-opted by agriculture declined from 90% to 70% during the 20th century (FAO 2006a, CAWMA 2007), and agricultural production of nonfood commodities, such as cotton and biofuel, is increasing (CAWMA 2007). Dietary shifts, forecasted to involve a per capita 25% increase in meat intake and a 10% increase in calories over the next decades (WHO 2003), result in more per capita water use, as meat production

BioScience 59: 967–976. ISSN 0006-3568, electronic ISSN 1525-3244. doi:10.1525/bio.2009.59.11.8

requires about 10 times more water per calorie than does grain production (Cohen 1995). Climate change forecasts show an increase in the frequency of droughts and floods across regions and greater variability in water availability and food insecurity across the planet (Easterling et al. 2007, Lobell et al. 2008), and the combined effect of population growth and climate change on water resources may exceed their independent effects (Vörösmarty et al. 2000). Land availability may become a constraint even where water is sufficient. At current yields, crop and grazing areas will have to increase by 50% to 70% to produce the food required to feed the projected human population in 2050 (CAWMA 2007). Yet crop area declined from 0.5 to 0.25 hectares (ha) per capita between 1960 and 2000 (CAWMA 2007), and according to critical assessments, new, available, cultivable land falls short of furnishing the needed area, particularly considering the loss of cropland caused by soil erosion, salinization, and the expansion of urban and industrial land (Young 1999, Döös 2002). These calculations and trends depict a likely scenario in which Earth's capacity to support the human population may be reached within the next decades, at population levels below currently proposed estimates.

Table 1. Annual production and current growth rates of agriculture, livestock, freshwater and marine aquaculture, and wild harvest of fisheries and aquatic plants.

Group	Annual production in 2004 (10^6 metric tons)	Production growth rate, 1994–2004 (percentage per year, plus or minus standard error)
Land		
Agriculture (nonfood items excluded)	7000	2.0 ± 0.1
Livestock (meat)	260	2.6 ± 0.1
Aquatic		
Cultured		
Freshwater animals	26	7.3 ± 0.4
Marine animals	20	7.4 ± 0.3
Marine plants	14	7.5 ± 0.5
Wild harvest		
Fisheries	96	0.1 ± 0.2
Aquatic plants	1.4	0.5 ± 0.6

Note: The specific growth rate in food production was calculated as the slope of the fitted regression equation between the natural log of food production versus time.

Source: FAO 2006c, 2006d.

The rise of aquaculture

Aquatic food production amounts to about 157×10^6 metric tons per year, about 2% of total food production, and provides about 16% of the protein humans consume. Fisheries catches have been declining over the past two decades (Pauly et al. 2003), and many stocks are currently overexploited (Myers and Worm 2003, Naylor and Burke 2005). Indeed, the global fish supply per capita has declined, and, by some estimates, current harvests remain twofold above the levels considered sustainable (Coll et al. 2008). Analyses of possible future scenarios for fisheries conclude that the trend toward declining fisheries yield can be reversed by a set of policy actions, including reduced fishing effort, a shift of catch effort and human consumption patterns toward small pelagics, a major expansion of marine reserves, and incentives to achieve sustainable use; such policies may allow catches to remain sustainable or even recover to the levels of the 1970s, before the decline began (Pauly et al. 2003, Hilborn et al. 2005).

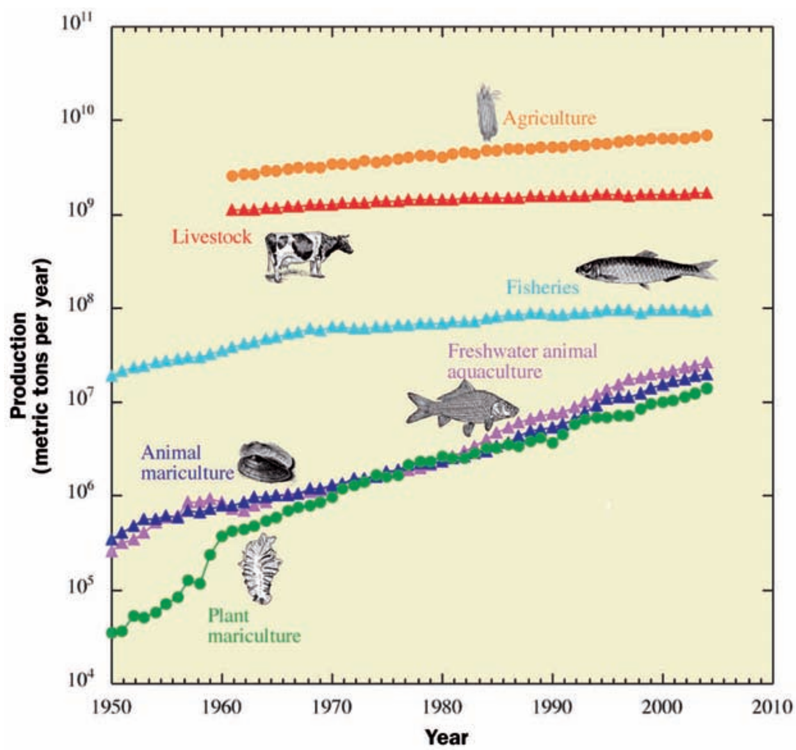

Figure 1. Trends in the global production of agriculture (nonfood items excluded), livestock (meat), freshwater and marine aquaculture, and fisheries over the past 50 years. Source: Data derived from the Food and Agriculture Organization (FAO 2006a, 2006c, 2006d).

In contrast, aquaculture production has grown steadily since its emergence as a significant food production sector five decades ago, at rates equivalent to about a doubling of production each decade; aquaculture now delivers 39% of aquatic food products (table 1, figure 1). The growth of aquaculture (> 7% per year; table 1) far exceeds that of population growth (0.5% per year; Lutz et al. 2001), as well as that of food production on land (about 2.0% per year; figure 1, table 1).

Mariculture production is dominated, by weight, by algae (46.2%), followed by bivalves (42.9%), diadromous (5.3%) and marine (3.7) fishes, and crustaceans (1.8%; figure 2). Over the last decade, the production of crustaceans, cultivated mostly in brackish waters, has shown the fastest growth (23% per year), twice that of diadromous (11.5% per year) and marine fishes (10.5% year), and almost four times that of bivalves (6.2% per year; figure 2).

The rise of aquaculture is a recent phenomenon facilitated by the rapid domestication of aquatic species (3% increase per year; Duarte et al. 2007)—449 species are domesticated, and there is ample market demand for the domestication of many more, as more than 3000 wild marine species are harvested for food (Duarte et al. 2007). The rapid, successful additions of newly domesticated species to the production process is apparent: The number of species contributing 90% of mariculture production increased from 14 to 20 between 1994 and 2004, compared with only 4 to 5 species delivering 90% of livestock production on land over the same time (table 2). The diversification of mariculture adds flexibility: It leads to diversification in the marine habitats and resources used to support production, and to a broad range of market prices for its products (Duarte et al. 2007), which have been in decline as a result of stepped-up production and competition among producers and countries (Naylor et al. 2003).

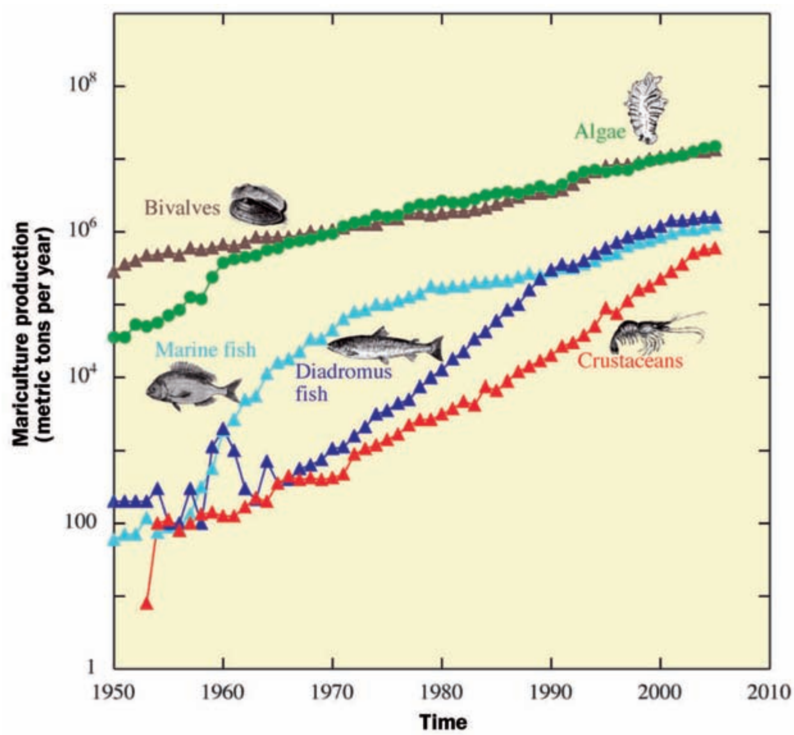

Figure 2. Global annual mariculture production of bivalves, crustaceans, algae, and diadromus and marine fish. Source: Data derived from the Food and Agriculture Organization (FAO 2006a).

Freshwater aquaculture, dominated by Chinese carp aquaculture (FAO 2006a), represents 57% of animal aquaculture production. Despite considerable intensification (e.g., a 10-fold increase in the yield of Chinese freshwater aquaculture in 20 years; FAO 2006a), freshwater aquaculture is increasingly spatially constrained in the tropics and subtropics because of rapid human population growth and the concomitant high requirements for direct use of water and land (FAO 2006a), although there is still room for expansion in northern temperate regions. Freshwater aquaculture also requires large amounts of freshwater to compensate for large losses through seepage and evaporation, comparable to that required for animal production on land. Thus, although there is still margin for significant growth in freshwater aquaculture (Diana 2009), such cultivation is unlikely to continue to grow in a future scenario of increasing water shortage (see Verdegem et al. 2006). Space and water constraints will most likely drive aquaculture growth toward mariculture in the long term (Verdegem et al. 2006, Olsen et al. 2008).

Mariculture is on the rise: Growth rates almost doubled in 10 years, and production increased 10-fold in 30 years (figure 3, table 1). Animal mariculture is on course to exceed fisheries catches and animal-protein production on land within two and five decades, respectively. Although the scope for aquaculture growth is still high (FAO 2006a, Diana 2009), there are significant challenges ahead. The FAO forecasts that mariculture will reach 54 million metric tons to 70 million metric tons by year 2020 (Delgado et al. 2003), close to the production predicted from direct extrapolation of the current 7.5% per year growth rate (figure 3). Further growth will run into major bottlenecks concerning the availability, suitability, and cost of feed; space availability; and adverse environmental impacts, which must be overcome if mariculture is to

Table 2. Number of species accounting for 50%, 90%, and 100% of global food production in agriculture, livestock, marine fisheries, and mariculture, and percentage change of species diversification during this period.

	Number of species in 1994			Number of species in 2004			Percentage change from 1994 to 2004		
Group	50%	90%	100%	50%	90%	100%	50%	90%	100%
Agriculture	5	29	150	5	30	150	0.0	3.4	0.0
Livestock	1	4	16	1	5	16	0.0	25.0	0.0
Marine fisheries	13	134	987	17	145	1324	30.8	8.2	34.1
Mariculture	3	14	146	5	20	180	66.7	42.9	23.2

Note: A few of the items in FAO food production reports do not correspond to individual species, but rather to aggregates of an undefined number of species. Therefore, the actual number of species contributing 50% and 90% of food production should be slightly above the number that appears in this table.

Source: FAO 2006a, 2006b, 2006c, 2006d.

become a major component of global food production (Marra 2005, Diana 2009).

The availability of feed for aquaculture

Fish and crustacean mariculture currently depend on the use of feeds derived from wild fisheries, which constitutes a major vulnerability. The amount of fish and shellfish from capture fisheries that is used annually to produce fishmeal, oils, and other products not used as human food has increased from 3 million to 28 million metric tons in 50 years (FAO 2006a). It takes 20 million to 25 million metric tons of fishmeal to produce 30 million metric tons of fish and crustaceans (Tacon et al. 2006).

The maximum possible yield of fishmeal and oil is estimated to cap fish and crustacean mariculture at 45 million to 50 million metric tons per year (figure 3; Olsen et al. 2008), a level that at current growth rates will be reached by 2040 (figure 4). A reduction in the use of fishmeal and oil can be achieved by substituting plant protein (e.g., soybean) for animal protein in feed for salmon and carnivorous fishes (Bell and Waagbø 2008). However, this strategy renders fish mariculture dependent on agriculture, which therefore makes it vulnerable to the bottlenecks in freshwater and land availability that agriculture will encounter. Hence, mariculture must be rendered independent of the use of agricultural products. Large zooplankton, such as *Calanus finmarchicus* in Nordic seas and Antarctic krill (*Euphausia superba*) in the Southern Ocean, provide an untapped resource (Olsen et al. 2008). However, dependence on external feed subsidies will not permit sustained growth over decades, which is the time frame required for mariculture to be able to help alleviate global food shortages (Olsen et al. 2008).

The absolute challenge that mariculture faces is to close its production cycle, as agriculture did in the 20th century; the food required to feed marine animals should be produced by mariculture rather than harvested from the wild or derived from agriculture. A first, most important step should be to boost the efficiency of aquaculture by lowering the trophic level of aquaculture products, as recommended for fisheries catches as well (Pauly et al. 2003). The efficiency of the use of feed to yield mariculture products varies across taxa, ontogenic status, and the protein content of the food. Considering the average growth efficiency in mariculture production to range from 15% to 35% (Welch 1968), a unit production of a given food web must be supported by about three to seven times as much supply of primary production as that required to achieve the same yield at a trophic position one step below. Mariculture production has a weighted mean trophic position of 1.898 (table 3), well below the value of 3.20 estimated for capture marine fisheries (Pauly et al. 1998), but much greater than the value of 1.03 calculated for agriculture and livestock production (figure 4, table 3). These differences imply that the primary production required to support a unit of wild fisheries and mariculture production are 34 and 2.4 to 4.8 times larger, respectively, than that for a unit of food production on land (figure 4). A reduction in the weighted-mean trophic position of mariculture production can be achieved by increasing the production of macroalgae as food for humans and herbivore organisms, such as filter feeders and herbivorous fishes, which are indeed the fastest-growing components of mariculture production (FAO 2006a; see above). A modest 0.4 unit reduction in the mean trophic position of mariculture should allow a doubling of the production for the same use of marine primary production. An additional approach is to combine species in integrated multitrophic mariculture, which improves the yield of aquaculture while reducing its environmental impact (Neori et al. 2004, Zhou et al. 2006). For example, the yield of

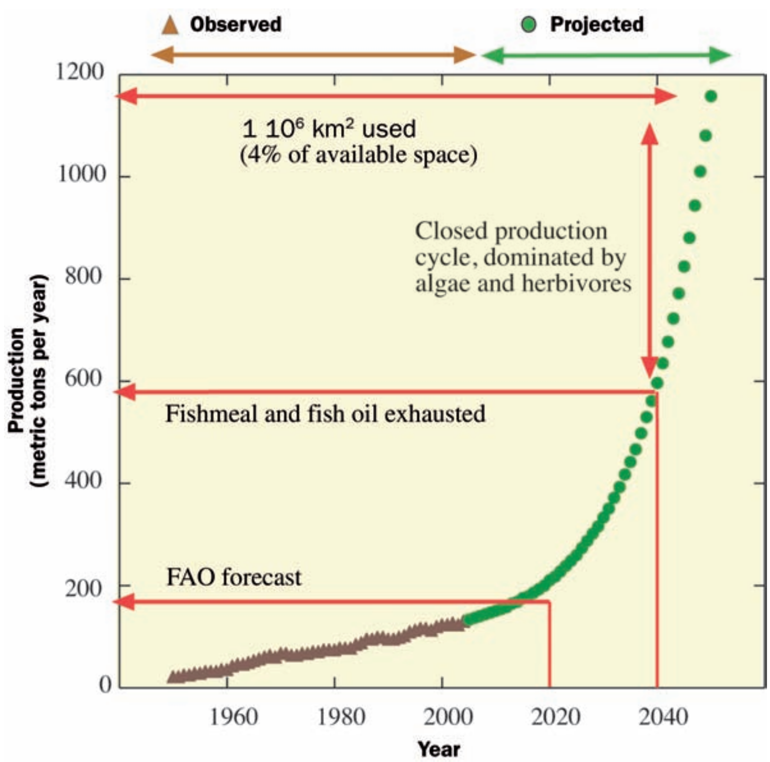

Figure 3. The time course of observed (brown triangles) and projected (green circles) marine food production and the bottlenecks and changes required to maintain growth. Observed marine food production includes mariculture products, wild fisheries, and harvest of natural macroalgal stocks (FAO 2006a). The projected food production was derived assuming wild fisheries and harvest of natural macroalgal stocks to be maintained at 2005 levels, and mariculture to maintain its current 7.5% per year growth. The figure shows the projected marine food production in 2020 (Delgado et al. 2003); the projected time at which fish feed to raise fish and crustaceans will be exhausted, estimated as the time at which the potential fish feed will be consumed; and the space occupied by mariculture, using present yields, at the projected production by 2050.

bivalves and macroalgae can increase by 15% and 50%, respectively, when they are cultured near fish farms, converting waste into bivalve and macroalgal biomass (Neori et al. 2004, Zhou et al. 2006). The combination of these options—reduction in the mean trophic level, use of alternative food products such as zooplankton and macroalgae, and integrated aquaculture—can boost aquaculture production at least eightfold over present levels (figure 3).

Space limitation

The availability of suitable space is already becoming a problem for aquaculture, as it is for agriculture, and may represent a growing bottleneck as mariculture production develops (Marra 2005, Olsen et al. 2008). In contrast to agriculture developed along private property, mariculture growth generally depends on the use of public coastal space, which puts it in competition with other societal demands such as infrastructure and leisure. Using very conservative estimates for current aquaculture yield (e.g., 16 tons per ha of shellfish, excluding shell weight, which can reach up to 500 tons per ha in long-line, high-density rafts, and 25 tons per ha for fish; FAO 2006b), a shelf area of 26 million square km (km^2) could support mariculture and off-shore aquaculture production of 3×10^{10} to 6×10^{10} metric tons (figure 3). The space now used for mariculture production, estimated from the production and yield figures given above, represents about 0.01 million km^2, or about 0.04% of the shelf area. Hence, even a 20-fold growth of mariculture production would require the use of less than 1% of the shelf area. However, this calculation considers mariculture to be randomly distributed over the continental shelf, whereas mariculture production is concentrated in a selected number of countries (e.g., China, Spain, Greece, Norway, Chile, and Scotland), particularly in sheltered bays and lagoons. Technological developments needed to safely extend mariculture operations into highly exposed, offshore locations are already emerging (Marra 2005). In addition, new international governance frameworks must be developed to ensure the shared and equitable use of the oceans (Marra 2005), which calls for further development of the UN Law of the Sea.

Environmental and health hazards

The global spread of aquaculture has had negative effects on biodiversity (e.g., Naylor et al. 2000, Holmer et al. 2008), recently reviewed by Diana (2009). Mariculture may also involve health hazards to humans (Durborow 1999). Persistent organic pollutants and heavy metals are found in fishmeals and oils, and they may accumulate in mariculture products, presenting a potential health risk to consumers (Holmer et al. 2008), although no more than does the consumption of wild marine predators. Reducing the dependence of mariculture on fish oils and fishmeal with closed-cycle and lower trophic-level mariculture will diminish the hazards associated with pollutants contained in fish feeds. Moreover, pollutants can be removed from fish oils by short-path solvent extraction, distillation, and adsorption onto active carbon, with only a minor impact on the price of the products (Maes et al. 2005). Marine bivalves and crustaceans may also contain pathogens and toxins that cause diarrhea in consumers (CNRS 2007). Most seafood-borne viruses probably originate from human sources (CNRS 2007), so reducing sewage inputs to coastal waters will also reduce health hazards from mariculture. Use of chemotherapeutants and nutrient supplements in mariculture feed leads to the input of these chemicals to the environment (CNRS 2007, Holmer et al. 2008), and anti-

Table 3. Trophic-level values for aquaculture, livestock, and marine capture fisheries.

Species	Production in 2004 (metric tons)	Trophic position
Red seaweeds	4,044,142	1
Miscellaneous aquatic plants	2,601,787	1
Oysters	4,603,145	2
Mussels	1,856,072	2
Salmons, trouts, smelts	1,551,736	3.5
Scallops, pectens	1,166,756	2
Miscellaneous marine molluscs	1,064,561	2.5
Miscellaneous coastal fishes	554,738	3.5
Shrimps, prawns	316,460	2.5
Marine fishes not identified	215,978	3
Miscellaneous pelagic fishes	188,568	3
Crabs, sea spiders	187,031	3
Flounders, halibuts, soles	109,012	3.5
Sea urchins and other echinoderms	60,852	2
Miscellaneous marine crustaceans	47,436	2.2
Miscellaneous aquatic invertebrates	42,159	2.3
Miscellaneous diadromous fishes	41,041	3.5
Sea squirts and other tunicates	21,442	2.3
Miscellaneous demersal fishes	19,708	3
Green seaweeds	19,046	1
Pearl oysters	13,021	2
Tunas, bonitos, billfishes	11,508	5
Cods, hakes, haddocks	3884	3.7
River eels	504	3
Lobsters, spiny-rock lobsters	39	3
Squids, cuttlefishes, octopuses	13	5
Total mariculture	18,740,639	1.898[a]
Agriculture	7,100,000,000	1
Livestock	260,000,000	2
Total terrestrial food sector	7,360,000,000	1.03
Marine capture fisheries	87,424,590	3.1[b]

Note: The trophic position of the aquaculture production was calculated using a trophic level value of 1 for primary producers and average values drawn from the literature for each species group (Hobson and Welch 1992, Pauly et al. 1998, Froese et al. 2004, Kaeriyama et al. 2004) or rough estimates when we did not find specific references. Production values for the terrestrial food sector and for mariculture were obtained from FAOStat (FAO 2006c) and FishStat (FAO 2006d), respectively.

a. Total mariculture trophic position was obtained as the weighted average of the trophic position of all species, weighted by their relative contribution to total production.

b. The value used here was taken from Pauly and colleagues (1998). However, calculations done with 2004 capture fisheries data (FAO 2006d) yield a slightly higher value (3.2); but again, we estimated trophic positions for several species—no modeling or direct evaluation with stable isotopes has been done.

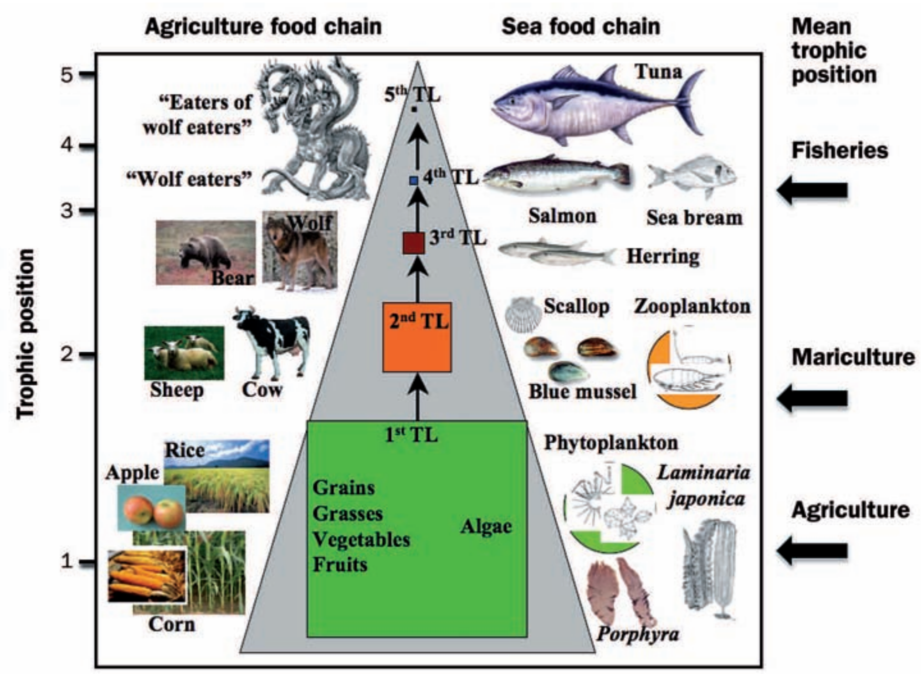

Figure 4. A comparison of the trophic position of agriculture and mariculture products, including idealized parallels of terrestrial equivalents to high trophic positions harvested at sea, along with the weighted-mean trophic position of wild fisheries, mariculture, and agriculture products (see table 3). Abbreviation: TL, trophic level.

biotic use may result in aquaculture reservoirs for antibiotic-resistant pathogens that may affect humans (CNRS 2007).

The environmental costs of mariculture are typically assessed by comparison with undisturbed control sites, but they are rarely compared with those of terrestrial agriculture (Diana 2009). The impacts of mariculture are modest when compared with those of food production on land (Diana 2009), which include global impacts derived from the production and application of fertilizers, pesticides, antibiotics, and growth hormones, as well as from animal-released methane (Tilman et al. 2001). Agriculture has transformed about 40% of the surface of the planet (Foley et al. 2005), causing significant environmental impacts (Ojima et al. 1994), compared with the 0.04% of shelf area used by mariculture. Indeed, agriculture-derived nutrient inputs are, and will continue to be, the major driving force of coastal eutrophication globally (Tilman et al. 2001), far more so than nutrients emitted by mariculture. The global nitrogen-use efficiency in animal production is slightly more than 10% (5% for beef and 15% for pork; Smil 2002), rendering livestock production a major source of nitrogen inputs to the environment (Smil 2002). In contrast, marine animals have much greater nitrogen-use efficiency, at about 20% for shrimp (Jackson et al. 2003) and 30% for fish (Smil 2002), so for any given production, mariculture releases two to three times less nitrogen to the environment than does livestock production. Domestication of land animals has been a vector for major diseases and pests that have decimated human populations in the past (Diamond 2001), and disease outbreaks associated with animal husbandry (e.g., mad cow disease, influenza) remain a risk to human health (Cleaveland et al. 2001, Fouchier et al. 2005). In contrast, only 10% of all foodborne illnesses in the United States are attributed to seafood consumption, which makes it a relatively safe food commodity (CNRS 2007). Whereas livestock production continues to use huge amounts of antibiotics, the development of vaccination techniques has reduced the use of antibiotics in salmon mariculture by more than 90% (Tidwell and Allan 2001).

This comparison suggests that mariculture has fewer impacts than agriculture, but the possible health and environmental hazards of mariculture are nonetheless vulnerable to misinformation, contributing to societal concerns and opposition from competing users of the coastal zone (e.g., the tourist industry), which act as significant barriers for mariculture growth (Holmer et al. 2008). The dioxin case—Scottish salmon produced in aquaculture were reported to contain high levels of dioxin (Hites et al. 2004)—created turmoil among producers, consumers, and competing sectors of the food industry until additional studies led the European Food Safety Agency to conclude that, "with respect to their safety for the consumer there is no difference between wild and farmed fish" (EFSA 2006).

Mariculture has the potential to help correct these problems and produce some positive effects for the environment (Diana 2009). Fish aquaculture is currently supplementing rather than replacing wild catches (Naylor and Burke 2005, Diana 2009), but with its contribution of 30% of marine food production, mariculture is helping to meet consumer demands and potentially reducing pressure on wild stocks. Thus, mariculture is making sustainable fisheries and an increased seafood supply compatible targets. Evidence for mariculture's reduction of pressure on wild stocks is still sparse, although it has been documented that cultured Atlantic salmon is contributing to the rebound of some local stocks of natural populations (Diana 2009). However, the potential beneficial effect of such alleviation of pressure on wild stocks will be fully realized only when the production cycle is closed within mariculture.

Mariculture has also been used to supplement wild stocks directly. For instance, the Alaska salmon fishery is highly dependent on the release of young fish reared in aquaculture (Tidwell and Allan 2001). However, there is evidence that such releases can affect the viability and productivity of supplemented populations (Reisenbichler and Rubin 1999). Mariculture's use as a tool to complement natural recruitment by helping the recovery of natural stocks and by catalyzing the recovery of endangered species should be developed further to reduce such impacts.

Macroalgal production helps remove excess nutrients and replenish oxygen in water, and the production of filter-feeder organisms reduces excess plankton, thereby alleviating the effects of eutrophication on coastal ecosystems. For example, the spread of blue mussel culture has been proposed as a mechanism for remediation of Baltic eutrophication (Lindahl et al. 2005). Moreover, mariculture of fish and shellfish is threatened by anthropogenic contaminants and toxins from harmful algal blooms, so the mariculture sector exerts political pressure to reduce contaminant inputs and maintain good water quality (Olsen et al. 2008).

Mariculture also helps maintain and improve human health. Important compounds specific to or abundant in the marine food web—omega-3, iodine, selenium, and proteins, for example—are recognized to convey health benefits, so a diet rich in marine food supports human health (Uauy and Valenzuela 2000, CNRS 2007). However, the World Health Organization's recommendation that humans ingest a median 450 grams of marine food per week (WHO 2003, CNRS 2007) means that the projected 9200 million people in the year 2050 would need 231 million tons of marine products annually, which is more than twice the amount that fisheries and marine aquaculture now produce. Although best practices can increase fisheries catches somewhat, only mariculture can deliver the major growth in marine food products required for a healthy diet. However, mariculture must remain closely connected to the marine food web if it is to continue to deliver the health benefits of a marine diet.

Toward integrated land and marine food production

Our analysis suggests that mariculture has the potential to help alleviate food shortages resulting from limited freshwater resources and arable land to support future agricultural growth, but to sustain its 7.5% per year growth rate, the sector must evolve beyond current practices and concepts to overcome the challenges and bottlenecks it encounters. The expansion of marine aquaculture over the next decades will require significant social, scientific, technological, and policy inputs (Marra 2005, Diana 2009). The use of fishmeal as fertilizer in agriculture or as food for livestock and in aquaculture should be abandoned. Moreover, the fish catches that support the production of fishmeal, such as sardines and anchovies, should be redirected to feed humans directly, thereby lowering the trophic level at which fisheries are harvested—an important requisite for recovering fisheries catches (Pauly et al. 2003), which must support the food requirements of the vastly expanded human population of the future. This redirection may require innovations in the canning industry, because vegetable oils now used in canning may not be available in sufficient quantities in the areas where these fisheries are located (e.g., Peru).

Likewise, mariculture should also abandon the use of agricultural products in marine animal feeds, which represents an indirect use of cropland and water and leads to competition between fish and humans for food. Mariculture should strive to close its production cycle and lower the trophic level of the production. These actions require a major expansion in the production of macroalgae, which is already taking place in some regions. For example, macroalgal production in China yields 1.5 million metric tons per year to be used as food for humans, feed for marine animals, and as industrial raw material. In one hotspot area in China, Sungo Bay (Shandong Province, eastern China), around 60,000 metric tons of the seaweed *Laminaria japonica* are produced (cf. Zhang et al. 2009). These cultivation systems are rapidly expanding and already extend to offshore locations up to 8 nautical miles offshore in Sungo Bay, where they are visible from space (figure 5). The increase in macroalgal culture is currently receiving an additional impetus from the emerging use of macroalgal crops for biofuel production (Hosain and Salleh 2008). Algae produce up to 250 times the amount of oil per unit of area as soybeans do (Hosain and Salleh 2008), and their production has none of the major problems that biofuel production from land crops entail (Groom et al. 2008). The drive toward intensive production of macroalgae for biofuels may help the development of improved models for the mass production required for closing aquaculture's production cycle.

Mariculture must be driven toward a more sustainable model through governmental regulation to minimize impacts on biodiversity (Diana 2009) by closing production cycles, lowering the trophic level of aquaculture products, minimizing waste through integrated policultures, and using renewable sources of energy and freshwater. The integration of marine energy, a promising untapped source of energy (Scruggs and Jacob 2009), and desalination has the potential to greatly reduce the footprint of aquaculture on energy and water use. This integration may already be within our reach—new systems that use ocean energy to desalinate water have just been developed (Fernández-López et al. 2009). The development of offshore mariculture will increase the energy demands of marine food production, calling for close monitoring of the energy efficiency of aquaculture production and the coupled development of technologies for offshore mariculture and for marine energy use.

The spread of mariculture is occurring in the 21st century, an era of sophisticated scientific understanding and environmental awareness. It should therefore be possible to ensure that mariculture's development does not reproduce the errors associated with the expansion of agriculture after the Industrial Revolution (Duarte et al. 2007). To progress toward a sustainable model, mariculture must develop and adopt best practices to avoid inflicting the huge environmental damages that the intensification of agriculture did (Marra 2005).

Neither land-based nor marine-based food production alone will suffice to feed humanity in the future. An intelligent integration of marine- and land-based food production is required to meet this essential goal. The optimal combi-

Figure 5. Macroalgal farms extend eight miles offshore in Sungo Bay, China. Photograph: Yngvar Olsen; image at Google Earth™.

nation is one that allocates the water-intensive components of human food to the ocean. Although animal meat products represent only 3.5% of food production, they consume 45% of the water used in agriculture (CAWMA 2007). Thus, producing most of the meat component of the human diet in the ocean will greatly expand the scope for growth of land agriculture without exceeding current levels of water use.

Indeed, using agriculture to deliver plant products and the oceans to deliver animal products (at lower trophic levels than mariculture or fisheries now produce) will be consistent with the structure of the land and marine food webs. Terrestrial food webs are pyramidal in shape and dominated by plant biomass. In contrast, the oceans contain only 2% of the plant biomass in the planet, and marine food webs support a large animal biomass dependent on a comparatively small pool of fast-growing plants (Gasol et al. 1997). Moreover, the oceans not only deliver water indirectly, embedded as marine food, to humanity; they also can supply humanity with a direct source of freshwater. Although desalinated marine water at present delivers only about 10 km^3 of water annually, this figure is rapidly growing (von Medeazza 2004). Much of this desalinated water is allocated to domestic use, thus increasing the share of freshwater resources available for agriculture and further helping in the production of crops for food. Hence, the oceans are already helping to feed humanity not just by producing food but also by delivering water for human consumption.

By 2050, the time the global human population is predicted to reach 9200 million, mariculture will have an even greater role to play in feeding humanity. Promoting the growth of mariculture is the responsibility of all of society. Society must therefore be prepared to face the major social changes that will be required to adapt to the forthcoming major revolution in food production: transferring the production of animal protein from land to the ocean (Marra 2005). In parallel, actions to restore declining fisheries yields should be adopted (Pauly et al. 2003, Hilborn et al. 2005) if we are to reap the benefits bestowed by the harvesting of wild stocks. These changes cannot be left to market self-regulation, which is flawed by hidden subsidies such as the costs of water use to agriculture and the costs of agriculture's adverse effects on the environment; instead, such changes depend on social and political leadership, informed by the best available independent scientific knowledge and prospective analyses. Marine aquaculture must meet these challenges for the oceans to become a major source of food for humans—indeed, to become the next revolution in human food provision.

Acknowledgments

This research was funded by the project SAMI, sponsored by the Framework Program of the European Union. We thank John Marra, James S. Diana, and an anonymous reviewer for useful comments.

References cited

Bell JC, Waagbø R. 2008. Safe and nutritious aquaculture produce: Benefits and risks of alternative sustainable aquafeeds. Pages 185–226 in Holmer M, Black K, Duarte CM, Marbà N, Karakasis I, eds. Aquaculture in the Ecosystem. Springer.

[CAWMA] Comprehensive Assessment of Water Management in Agriculture. 2007. Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. Earthscan.

Cleaveland S, Laurenson MK, Taylor LH. 2001. Diseases of humans and their domestic mammals: Pathogen characteristics, host range and the risk of emergence. Philosophical Transactions of the Royal Society B 356: 991–999.

Cohen JE. 1995. How Many People Can the Earth Support? Norton.

[CNRS] Committee on Nutrient Relationships in Seafood. 2007. Seafood Choices: Balancing Benefits and Risks. National Academies Press.

Coll M, Libralato S, Tudela S, Palomera I, Pranovi F. 2008. Ecosystem overfishing in the ocean. PLoS ONE 3: e3881. doi:10.1371/journal.pone.0003881

Delgado CL, Wada N, Rosegrant MW, Meijer S, Ahmed M. 2003. Fish to 2020: Supply and Demand in Changing Markets. International Food Policy Research Institute, WorldFish Center. (28 October 2009; *www.ifpri.org/sites/default/files/publications/oc44.pdf*)

Diana JS. 2009. Aquaculture production and biodiversity conservation. BioScience 59: 27–38.

Diamond J. 2001. Evolution, consequences and future of plant and animal domestication. Nature 418: 700–707.

Döös BR. 2002. Population growth and loss of arable land. Global Environmental Change 12: 303–311.

Duarte CM, Marbà N, Holmer M. 2007. Rapid domestication of marine species. Science 316: 382.

Durborow RM. 1999. Health and safety concerns in fisheries and aquaculture. Occupational Medicine 14: 373–406.

Easterling WE, et al. 2007. Food, fibre and forest products. Pages 273–313 in Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE, eds. Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge University Press.

[EFSA] European Food Safety Authority. 2006. Opinion of the CONTAM Panel Related to the Safety Assessment of Wild and Farmed Fish. (27 October 2009; *www.efsa.europa.eu/en/science/contam/contam_opinions/1007.html*)

Falkenmark M. 1997. Meeting water requirements of an expanding world population. Philosophical Transactions of the Royal Society B 352: 929–936.

Fernández-López C, Viedma A, Herrero R, Kaiser AS. 2009. Seawater integrated desalination plant without brine discharge and powered by renewable energy systems. Desalination 235: 179–198.

[FAO] Food and Agriculture Organization. 2006a. The State of World Aquaculture. FAO Fisheries technical paper 5005. (28 October 2009; *www.fao.org/docrep/009/a0874e/a0874e00.htmI*)

———. 2006b. FIGIS-Aquaculture Web Page (28 October 2009; *www.fao.org/fishery/figis/en)*

———. 2006c. FAOSTAT (27 October 2009; *http://faostat.fao.org/site/408/default.aspx*)

———. 2006d. FISHSTAT. (27 October 2009; *www.fao.org/figis/servlet/static?xml=FIDI_STAT_org.xml&dom=org&xp_nav=3,1,2&xp_banner=fi*)

Field CB, Behrenfeld MJ, Randerson JT, Falkowski P. 1998. Primary production of the biosphere: Integrating terrestrial and oceanic components. Science 281: 237–240.

Foley JA, et al. 2005. Global consequences of land use. Science 309: 570–574.

Fouchier R, Kuiken T, Rimmelzwaan G, Osterhaus. 2005. A global task force for influenza. Nature 435: 419–420.

Froese RS, Garthe S, Piatkowski U, Pauly D. 2004. Trophic signatures of marine organisms in the Mediterranean as compared with other ecosystems. Belgian Journal of Zoology 134: 31–36.

Gasol JM, del Giorgio PD, Duarte CM. 1997. Biomass distribution in marine planktonic communities. Limnology and Oceanography 42: 1353–1363.

Groom MJ, Gray EM, Townsend PA. 2008. Biofuels and biodiversity: Principles for creating better policies for biofuel production. Conservation Biology 22: 602–609.

Hilborn R, Orensanz JM, Parma AM. 2005. Institutions, incentives and the future of fisheries. Philosophical Transactions of the Royal Society B 360: 47–57.

Hites RA, Foran JA, Carpenter DO, Hamilton MC, Knuth BA, Schwager SJ. 2004. Global assessment of organic contaminants in farmed salmon. Science 303: 226–229.

Hobson KA, Welch HE. 1992. Determination of trophic relationships within a high Arctic marine food web using d^{13} C and d^{15} N analysis. Marine Ecology Progress Series 84: 9–18.

Holmer M, Black K, Duarte CM, Marbà N, Karakasis I. 2008. Aquaculture in the Ecosystem. Springer.

Hosain ABMS, Shalleh A. 2008. Biodiesel fuel production from algae as renewable energy. American Journal of Biochemistry and Biotechnology 4: 250–254.

Jackson C, Preston N, Thompson PJ, Burford M. 2003. Nitrogen budget and effluent nitrogen components at an intensive shrimp farm. Aquaculture 218: 397–411.

Kaeriyama M, Nakamura M, Edpalina J, Bower R, Yamaguchi H, Walker RV, Myers KW. 2004. Change in feeding ecology and trophic dynamics of Pacific salmon (*Oncorhynchus* spp.) in the central Gulf of Alaska in relation to climate events. Fisheries and Oceanography 13: 197–207.

Lindahl O, Hart R, Hernroth B, Kollberg S, Loo LO, Olrog L, Rehnstam-Holm AS, Svensson J, Svensson S, Syversen U. 2005. Improving marine water quality by mussel farming: A profitable solution for Swedish society. Ambio 34: 131–138.

Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL. 2008. Prioritizing climate change adaptation needs for food security in 2030. Science 319: 607–610.

Lutz W, Sanderson W, Scherbov S. 2001. The end of population growth. Nature 412: 543–545.

Maes J, De Meulenaer B, Van Heerswynghels P, De Greyt W, Eppe G, De Pauw E, Huyghebaert A. 2005. Removal of dioxins and PCB from fish oil by activated carbon and its influence on the nutritional quality of the oil. Journal of American Oil Chemists Society 82: 593–597.

Marra J. 2005. When will we tame the oceans? Nature 436: 175–176.

Myers RA, Worm B. 2003. Rapid worldwide depletion of predatory fish communities. Nature 423: 280–283.

Naylor R, Burke M. 2005. Aquaculture and ocean resources: Raising tigers of the sea. Annual Review of Environment and Resources 30: 185–218.

Naylor R, Eagle J, Smith W. 2003. Salmon aquaculture in the Pacific Northwest: A global industry with local impacts. Environment 45: 18–39.

Naylor RL, Goldburg RJ, Primavera JH, Kautsky N, Beveridge MCM, Clay J, Folke C, Lubchenco J, Mooney H, Troell M. 2000. Effect of aquaculture on world fish supplies. Nature 405: 1017–1024.

Neori A, Chopin T, Troell M, Buschmann AH, Kraemer GP, Halling C, Shpigel M, Yarish C. 2004. Integrated aquaculture: Rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. Aquaculture 231: 361–391.

Ojima DS, Galvin KA, Turner BL. 1994. The global impact of land-use change. BioScience 44: 300–304.

Olsen Y, Otterstad O, Duarte CM. 2008. Status and future perspectives of marine aquaculture. Pages 293–319 in Holmer M, Black K, Duarte CM, Marbà N, Karakasis I, eds. Aquaculture in the Ecosystem. Springer.

Pauly D, Trites AW, Capuli E, Christensen V. 1998. Diet composition and trophic levels of marine mammals. ICES Journal of Marine Science 55: 467–481.

Pauly D, Alder J, Bennet E, Christensen V, Tyedmers P, Watson R. 2003. The future for fisheries. Science 203: 1359–1361.

Reisenbichler RR, Rubin SP.1999. Genetic changes from artificial propagation of Pacific salmon affect the productivity and viability of supplemented populations. ICES Journal of Marine Science 56: 459–466.

Scruggs J, Jacob P. 2009. Harvesting ocean wave energy. Science 323: 1176–1178.

Smil V. 2002. Nitrogen and food production: Proteins for human diets. Ambio 31: 126–131.

Tacon AGJ, Hasan MR, Subasinghe RP. 2006. Use of Fishery Resources as Feed Inputs for Aquaculture Development: Trends and Policy Implications. FAO Fisheries Circular no. 1018.

Tidwell JH, Allan JL. 2001. Fish as food: Aquaculture's contribution. EMBO Reports 2: 958–963.

Tilman D, Fargione J, Wolff B, D'Antonio C, Dobson A, Howarth R, Schindler D, Schlesinger WH, Simberloff D, Swackhamer D. 2001. Forecasting agriculturally driven global environmental change. Science 292: 281–284.

Uauy MD, Valenzuela A. 2000. Marine oils: The health benefits of n-3 fatty acids. Nutrition 16: 680–684.

[UN] United Nations. 2007. World Population Prospects: The 2006 Revision Population Database. (27 October 2009; *esa.un.org/unpp*)

Verdegem MCJ, Bosma RH, Verreth JAV. 2006. Reducing water for animal production through aquaculture. International Journal of Water Resources Development 22: 101–113.

von Medeazza GM. 2004. Water desalination as a long-term sustainable solution to alleviate global freshwater scarcity? A North-South approach. Desalination 169: 287–301.

Vörösmarty CJ, Green P, Salisbury J, Lammers RB. 2000. Global water resources: Vulnerability from climate change and population growth. Science 289: 284–288.

Welch HE. 1968. Relationships between assimilation efficiencies and growth efficiencies for aquatic consumers. Ecology 49: 755–759.

[WHO] World Health Organization. 2003. Food based dietary guidelines in the WHO European Region. WHO.

Young A. 1999. Is there really spare land? A critique of estimates of available cultivable land in developing countries. Environment, Development and Sustainability 1: 3–18.

Zhang J, Hansen PK, Fang J, Wang W, Jiang Z. 2009. Assessment of the local environmental impact of intensive marine shellfish and seaweed farming—application of the MOM system in the Sungo Bay, China. Aquaculture 287: 304–310.

Zhou Y, Yang HS, Hu HY, Liu Y, Mao YZ, Zhou H, Xu XL, Zhang FS. 2006. Bioremediation potential of the macroalga *Gracilaria lemaneiformis* (Rhodophyta) integrated into fed fish culture in coastal waters of north China. Aquaculture 252: 264–276.

Carlos M. Duarte (carlosduarte@imedea.uib-csic.es) is a research professor at the Instituto Mediterráneo de Estudios Avanzados, Consejo Superior de Investigaciones Científicas/Universidad de las Islas Baleares, Esporles, Spain, where Núria Marbà is a researcher and Joana Guiu is an assistant. Marianne Holmer is a professor at the Institute of Biology, University of Southern Denmark, Odense. Yngvar Olsen is a professor in the Department of Biology of the Norwegian University of Science and Technology in Trondheim. Doris Soto is the senior fisheries officer at the Inland Water Resources and Aquaculture Service of the FAO Fisheries Department, Rome, Italy. Kenny Black is the head of the Ecology Department of the Scottish Association for Marine Science at Dunstaffnage Marine Laboratory, Oban, United Kingdom. Ioannis Karakassis is a professor in the Department of Biology of the University of Crete, Heraklion, Greece.