6. Discussion and conclusions

6.1 Analytical approach

Overall, the analytical approach is flexible and expandable in that it can be readily modified to encompass new species and advances in culture practices individually or collectively, as well as take on improved or new data sets and additional criteria and constraints for development. Further, as demonstrated in this document, species and culture systems can be combined for IMTA.

An important question concerns the reliability of the estimates of offshore mariculture potential. In general, they are the result of a sequence of informed decisions based on the literature, contacts with mariculture experts, and on mariculture practice. The sequence of decisions began with the key assumptions about the near-future development of offshore mariculture (Box 2). The key assumptions set the stage for the identification of analytical criteria (Table 1). The analytical criteria then led to the choice of species and culture systems, and finally to the thresholds that were at the core of the spatial analysis (Table 1). Two key assumptions fundamentally shaped the spatial analyses: cages and longlines as the offshore culture systems, and fish and mussels with already proven culture technologies and established markets as the animals to be grown out offshore (Box 2). Clearly, the ranges within species and culture system thresholds substantially influenced the results. For this reason, each threshold was reported individually in order to illustrate its influence on the overall results. The effects of modifications of thresholds for the Atlantic salmon and blue mussel on offshore mariculture potential were made evident in Section 4.5. It is important to mention that the species-culture system thresholds are broadly indicative of offshore mariculture potential of the selected species as well as species with similar temperature and food availability thresholds, not predictions of offshore success of the selected species. For that, many more variables would have to be included in the assessment. Finally, the stepwise process emphasizes the importance of thorough literature reviews, contacts with experts, and information from mariculture practice in order to specify ranges that will identify areas that are favourable for offshore mariculture development.

Potential was identified in terms of locations, and quantified as surface areas meeting criteria in aggregate globally and for the 20 mariculture nations and non-mariculture nations ranking highest for the criteria. One measure of reliability is the original resolution of the data. As shown in Annex 1, Table A1.1 and presented in Annex 1, bathymetry is at a relatively high resolution of ~0.9 km, while temperature (~4.9 km), chlorophyll-*a* (~4.6 km) and current speed (~8.9 km) are at lesser resolutions. Thus, places where offshore potential has been identified are indicative of potential in the vicinity, not of pinpoint locations of potential. The estimates also are affected by the depths at which the original data were acquired. Temperature and chlorophyll-*a* are from the near surface owing to satellite-borne sensor limitations. In contrast, current speed estimates with global coverage were available at a minimum depth of 30 m, while the upper depth threshold for cages and longlines was set at 25 m. As a consequence, there are areas in the 25–30 m depth range that meet the cage and longline depth thresholds for which there is no current speed coverage. The result overall is that potential may be somewhat underestimated with regard to the effect of current speed. Variability in time is another consideration. Data were analysed on monthly time steps (Annex 1). In this regard, bathymetry is not likely to vary significantly with that time step. In contrast, temperature, chlorophyll-*a* and current speed are time variable. Current speed is likely to be the most variable in relation to the one-month time step of this study. In order to provide a statistical basis for the temperature, chlorophyll-*a* and current speed thresholds, 95 percent confidence intervals were generated around the mean values. An area would be considered to fall within a threshold if the full confidence interval around the observed value at that location was completely within the upper and lower threshold values (Annex 1).

An additional measure of reliability is the time span of records for the time-variable data. In this regard, temperature covered 17 years, current speed 5 years, and chlorophyll-*a* 7 years: however, chlorophyll-*a* was not available for five months in each hemisphere during the coolest time of the year. The result is that actual chlorophyll-*a* concentrations during the months without coverage may be less than the 0.5 mg/m^3 threshold. Yet another consideration is the amount of missing data within data streams because of the lack of coverage by satellite sensors. Despite this constraint, because the data were aggregated by the month based on daily capture, the probability is high for most locations to be well represented.

In spatial studies employing many criteria and constraints, it is the usual practice to place weights on the criteria in different categories to determine the relative importance for each criterion (e.g. Aguilar-Manjarrez and Nath, 1998; Nath *et al.*, 2000). In this technical paper, criteria were not weighted because each one of them is considered to be the *sine qua non* for offshore mariculture development. Improvements in the approach by modifying thresholds within criteria, another kind of weighting process, are discussed in Section 6.3.

6.2 Comparisons of offshore mariculture potential with inshore mariculture practice and verification

Estimates of offshore mariculture potential require verification in order to be credible and useful for development planning. As noted in Chapter 1, offshore mariculture is in its infancy, and, as a consequence, locations are scarce where offshore mariculture already is established for the three species in this study. Verification by comparing predicted offshore mariculture potential with actual offshore locations was possible only for cobia and at only four farm sites. Verification by comparing the natural geographic ranges of the three species with the areas predicted to have potential was considered. However, there are a number of problems. One is that the distribution maps themselves are not fully reliable. For example, the Center for Quantitative Fisheries Ecology maps the worldwide distribution of cobia in terms of relative likelihood of occurrence that can range from .01 to 1.00, indicating that in many instances the actual geographic range is uncertain (CQFE, 2012). Also, there may be a general problem with migratory fish. That is, an area that migrants occupy seasonally may not be suitable for their offshore culture throughout the year. In the case of the Atlantic salmon, there is another problem. Because of the introductions into new areas for culture (e.g. Australia, Pacific Canada, Republic of Chile), the natural range would not correspond to areas where potential was found outside of that range. In the case of the blue mussel, the exact range is not known because of the confusion with other very similar *Mytilus* (FAO, 2012). In fact, the blue mussel distribution map in the above-mentioned fact sheet shows its natural distribution in Ireland and in the Kingdom of Norway where offshore mariculture potential was found, but the same map does not show its distribution in the eastern Canadian provinces where it is cultivated nor in the adjacent northeastern states of the United States of America where it is also farmed to a small extent.

Other instances, where inshore mariculture was in close proximity to offshore mariculture potential, provided an indicative verification in the sense that offshore temperatures were similar to those experienced in inshore mariculture and that the offshore chlorophyll-*a* concentration threshold was met in areas offshore of inshore blue mussel culture. For Atlantic salmon and blue mussel, the causes of a lack of coincidence between the initial estimates of offshore potential and the locations of farming areas or farm sites in some regions were identified. Temperature and chlorophyll-*a* data were acquired from culture sites, and temperature and chlorophyll-*a* from nearby offshore areas were sampled from archived spatial data. With these data to hand, thresholds were modified to better reflect offshore mariculture potential. Once adjustments had been made to the thresholds, the predictive ability of the criteria for assessing mariculture potential was greatly improved.

The inshore-offshore comparisons lent considerable credibility to the estimates of potential for offshore mariculture development. A general conclusion was that, where inshore mariculture was already established, oftentimes there was offshore mariculture potential meeting all or nearly all of the criteria. In such cases, the presence of inshore mariculture would provide a development advantage for offshore mariculture in that technologies, goods and services and access to markets currently supporting inshore mariculture would already be available for extension to offshore mariculture development.

In conclusion, the verification and comparison exercises showed that, despite the limitations of the data, the results are sufficiently reliable for the objectives, namely to comprehensively and comparatively deliver locations and surface areas of offshore mariculture potential aggregated globally that are a first approximation of offshore mariculture potential at the national level. These estimates of offshore mariculture potential await the addition of many more criteria and spatial analyses at higher resolutions to be undertaken at a national level.

6.3 Improvements in the approach

Improvements in the approach could be made in two basic ways: one is through modifications of the analytical approach using the same spatial data sets that were employed herein, and the other way is by adding new criteria and new data sets. For the former, using shorter time steps for temperature is one improvement that could be made, with eight-day intervals as the next available time step in the archived data as compared with the one-month time steps used herein. Another innovation, either with the present one-month time step, or a shorter one, would be to identify the worst and best case sequences of temperature affecting grow-out based on the 17-year archive of SST data used in this study (Annex 1, Table A1.1). Using the current data set, it would be possible to create additional thresholds (additional classes within criteria) so that potential could be expressed in increasingly better levels of suitability. For example, temperature thresholds could be classified to indicate areas with increasingly improved prospects for rapid growth, and the cost-effective area could be further classified by distance from a port as was carried out by Kapetsky and Aguilar-Manjarrez (2007, 2010) for the eastern EEZ of the United States of America.

The approach also could be expanded by adding attributes to the spatial data sets used in this study. For example, depth thresholds could be created in relation to cage mooring installation and maintenance costs. The cost-effective area, which takes into account time-distance expenses for servicing offshore installations, could be varied from nation to nation by using fuel and labour costs as attributes. These attributes could then be used to modify the cost-effective area for development in relation to port locations.

The final way in which the approach could be improved would be to add criteria based on additional data sets that possess a global scope. One of these is wave climate. Attention was called to the calculation of the wave climate for offshore cage culture by Pérez, Telfer and Ross (2003). James and Slaski (2006) showed that wave climate is a prime consideration for cultivating fish offshore. The cage structure and nets undergo structural loads, wear and fatigue and, ultimately, failure. For the cultured fish, excessive wave action can cause physiological problems, reduced growth, physical damage and mortalities. In addition to the aspects mentioned above, wave height is important in several ways, including access by boat to and from offshore installations and for the physical security of personnel working on the boats and installations. Additionally, cages and longlines are submerged in order to establish a depth at which wave influences will not be harmful to fish and shellfish during storms. The depth of submergence is related to wave height that, in turn, influences installation and maintenance costs. Wave height, one of the aspects of wave climate, was considered as a criterion for the present study. The global monthly mean significant wave height (SWH) data based on satellite altimetry, mentioned by Queffeulou, Bentamy and Croizé-Fillon (2010), are at a 2 degree resolution (330 km at the equator) that is much coarser than the other data sets used in this technical paper (see Dean and Salim, Annex 3, Section 5.2). Mean monthly SWH with global coverage averaged for 2009 were provided by the IFREMER Laboratoire d'océanographie spatiale (P. Queffeulou personal communication, 2012) with the caveats of complications from sampling and spatial variability of wave height. A preliminary analysis showed that, as a consequence of the coarseness, there was mean 2009 SWH coverage of only 73 percent of the global EEZ area. The same SWH data set covered 72 percent of the area with temperatures suitable for Atlantic salmon and depths and current speeds suitable for cages. In comparison, the SWH coverage was 60 percent of the area with temperatures suitable for cobia and depths and current speeds suitable for cages. Nevertheless, the potential usefulness of SWH data for assessing offshore mariculture potential was shown by a comparison of SWH ranges between the areas with potential for Atlantic salmon and cobia (Table 14).

TABLE 14

Mean SWH ranges in 2009 in areas suitable for offshore mariculture of Atlantic salmon and cobia

Mean SWH range in 2009 (m)		< 1	1–2	2–3	3–4	4–5
Atlantic salmon	Area (km^2) in the range	0	157	8 434	9 903	3 475
	Percent of area in the range	0	1	38	45	16
Cobia	Area (km^2) in the range	44 140	395 999	29 495	0	0
	Percent of area in the range	9	84	6	0	0

These results, although quite limited by spatial and temporal coverage, suggest that average annual SWH is several metres higher in areas suitable for salmon than in areas suitable for cobia, with multiple implications for culture structures and cultured fishes between the two kinds of offshore mariculture development. Other wave climate measures have been created in the KNMI/ERA-40 Wave Atlas (Caires, *et al.*, 2004) that is a climatology of wave climate including SWH and wave period the latter an important parameter for offshore culture structures. The estimates are based on data averaged on a 1.5°x1.5° area and the ocean wave data are only valid in deep water regions. Nevertheless, these wave-climate measures should be pursued in future studies.

Global data sets could be useful in several ways as extensions of the present study. One way is to place offshore mariculture in the broad context of status of oceans. The Global Ocean Health Index provides a vehicle by measuring the ocean's overall condition within the EEZ of each country on the basis of ten goals and with accompanying data layers (Halpern *et al.*, 2012). Another global data set that could be used to illustrate competing and conflicting uses, as well as to indicate water quality is described by Halpern *et al.* (2008) as part of the multicriteria Global Map of Human

Impact on Marine Ecosystems. The most relevant individual digital maps described by Halpern *et al.* (2008) are shipping activity and ocean pollution at nominal resolutions of 1 km^2. Another useful global data set, this one in tune with the ecosystem approach to aquaculture (EAA) development, is the Global 200 data set of Olson and Dinnerstein (2002). The Global 200 are the ecoregions that harbour exceptional biodiversity, of which there are 43 marine priority regions as well as terrestrial and freshwater ecoregions. The importance of these ecoregions in relation to aquaculture was summarized by Kapetsky, Aguilar-Manjarrez and Soto (2010). The Global 200 ecoregions were used by Kapetsky and Aguilar-Manjarrez (2008) as an example of the loss of potential for offshore culture of cobia by excluding areas suitable for cobia from the Global 200 marine ecoregions. About one-third of the global area with potential for good growth of cobia in sea cages at 25–100 m depths would be lost by using the marine Global 200 ecoregions of the world as a constraint.

The potential impact of climate change on aquaculture was assessed by De Silva and Soto (2009). In the marine realm, the potential impact of climate change on offshore mariculture could be investigated mainly through forecasting changes in locations and quantities of areas with offshore mariculture potential in relation to changing ocean temperature, ocean chemistry and primary production, and locational shifts in storm events.

6.4 Offshore mariculture potential

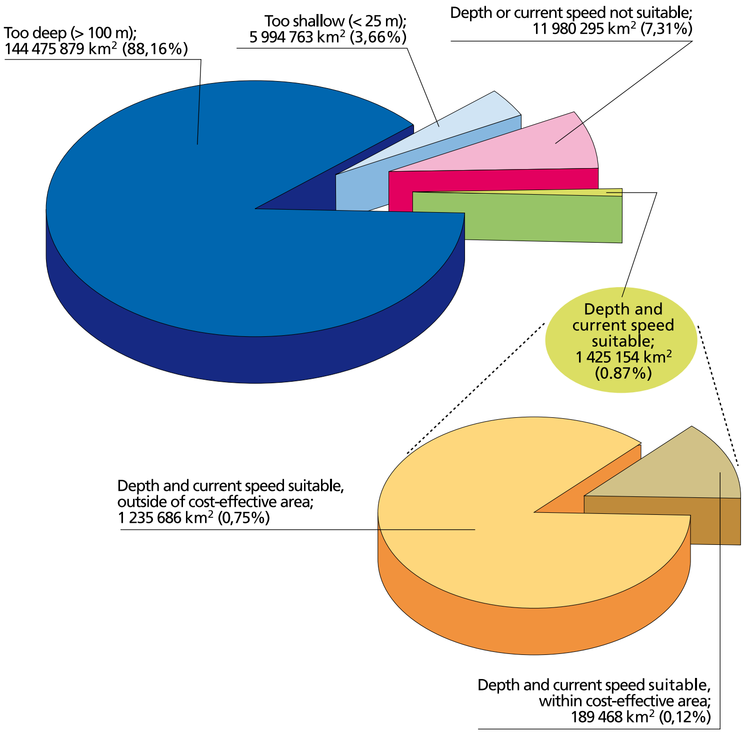
This study is based on the technical requirements of culture systems that will be important in the near-future development of offshore mariculture as well as on several representative species generally indicative of finfish and mussel offshore potential. The study shows that basic criteria can be used for a spatially quantitative view of indicative actual and near- future offshore mariculture potential at global and national levels. One of the major benefits of this study is that it provides, for the first time, estimates of the status and potential of offshore mariculture that are comprehensive of all maritime nations and comparable among them.

The results of this study indicate large, unrealized offshore mariculture potential from a spatial perspective. There are several lines of supporting evidence in this regard. The first line of evidence comes from the present status of mariculture (Chapter 2). The results pertain mainly to inshore mariculture. These results show that, in all, 93 countries and territories practised mariculture during the period 2004–2008, and that there were 72 maritime countries and territories (44 percent of the total) that were not yet practising it. Those already practising mainly inshore mariculture are doing so with highly varying intensities of production, ranging from a fraction of a tonne per kilometre of shoreline to more than 500 tonnes per kilometre of shoreline (Figure 4). One-half of those nations or territories are producing at less than 1 tonne per kilometre of coastline, suggesting that mariculture could be expanded in many countries.

A second line of supporting evidence also indicates large offshore mariculture potential in absolute terms. The evidence comes from the results of the spatial analysis of the basic technical and economic criteria upon which offshore development must depend (i.e. depths and current speeds for cages and longlines and cost-effective area for development) (Section 4.4). These criteria, in broad terms, represent the present limits of offshore technologies and offshore operational reach in cost-distance terms. The overall situation is summarized in Figure 50. Assuming that global offshore mariculture potential is represented by the aggregate global area within EEZs, there would be nearly 164 million km^2 available for development, with all other uses set aside. However, in relative terms, near-future offshore mariculture is severely limited by the need to tether cages and longlines to the seafloor in that about 92 percent of the EEZ area is either currently too deep or too shallow for cages and longlines. In 7 percent of the EEZ area, either depth or current speed is suitable, but there is no spatial overlap

FIGURE 50

Areas (km^2) within EEZs relative to depths and current speeds suitable for sea cages and longlines and to the cost-effective area for development



between the two criteria. The area with both depth and current speed suitable beyond the cost-effective area for development represents only about 0.9 percent of the total EEZ area. However, this area is quite large in absolute terms, about 1.4 million km^2. With the cost-effective area for development taken into account together with suitable current speed and depth, the area suitable for development in technical and cost-effective distance terms is about 0.1 percent of the total EEZ area, but this, too, is absolutely large, nearly 190 000 km^2. This measure corresponds to the offshore potential to be realized beginning in the immediate future and extending for years to come while taking into account that offshore installations are bound to shore-based services. Given that the cost-effective area employed in this study is only broadly indicative of the economic limiting distance for offshore development, this still represents a vast area within reach of present technologies with all other uses and other limiting criteria set aside. As autonomy and other technologies are improved, this area will expand seaward.

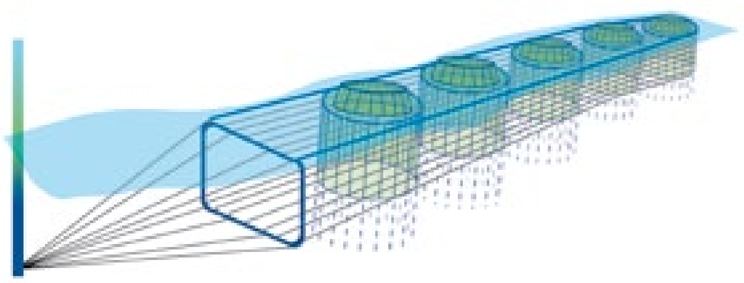
Improvements in mooring systems could further expand offshore mariculture potential. Goudey *et al.* (2001) note that a single-point mooring (Figure 51) could reduce the anchoring costs of a cage operation by 50 percent compared with the then current multianchor methods.

Single-point mooring cost reduction is due to reduced hardware installation and maintenance costs. Assuming that the cost savings of the single-point mooring of sea cages would result in technical and economic feasibility for up to 150 m compared with the 100 m limit used in this study, then the additional area with potential would expand by 4.2 million km^2, current speed limitations set aside. This is a considerable increase, 31 percent, over the 13.4 million km^2 area in the 25–100 m depth range.

Yet another view of unrealized offshore mariculture potential relates to divorcing offshore installations from their present dependence on being moored. Free-floating and propelled installations represent offshore mariculture potential for the future. Although there is a relatively small proportion of the global EEZ area that is within the present depth limits of moored cages and longlines, there is a vast area with potential for mariculture using free-floating and propelled installations as envisioned by Wilcox (1982), Loverich and Goudey (1996), Goudey (1998a and 1998b), and Goudey *et al.* (2001). Recently, the Velella Project tested an untethered, free-floating Aquapod net pen culturing kampachi (*Seriola rivoliana*) in the waters offshore from the Big Island of Hawaii (Plate 6). The Velella Project ranged from 3–75 nm (5.5–138.9 km) offshore, in waters up to 4 000 m deep, with a combination of passive drift and towing from a steel-hulled schooner, which acted as the tender vessel, dive platform and feed barge (Sims and Key, 2012).

As noted by Loverich and Goudey (op. cit.), the Ocean Drifter would drift with ocean and coastal currents, but have the capability for self-propulsion. The conceptual design of Goudey *et al.* (2001) has a normal draft of 45 m. Allowing a 5-m margin for safety, the space available for such an installation, globally aggregated within EEZs, amounts to about 153 million km^2. Another similar design of the Ocean Drifter is pictured by Ryan (2004), that one with a 24-m draft (Figure 52). Taking 25 m as the minimum depth for that version, the area available would be nearly 158 million km^2. The areas most suitable for Ocean Drifters would be those that experience reciprocal tidal currents or gyres in order to maintain ideal conditions for growth (Loverich and Goudey, op. cit.). Placement within predictable ocean currents constitutes another possibility for mobile cages (Goudey, 2009). This requirement could greatly limit the area that is actually suitable for free-floating and propelled cages, as compared with the vast area potentially available within the EEZs mentioned above.

FIGURE 51
Idealized diagram of a multiple sea cage system with a single point mooring

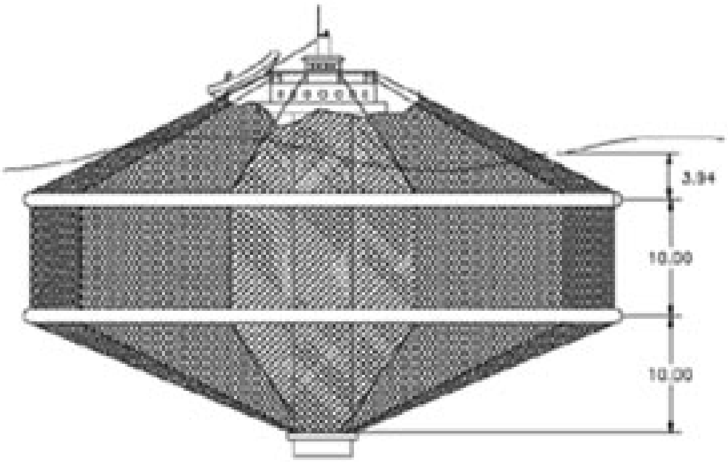


Source: SUBFlex (2011).

PLATE 6
Experimental version of an offshore towed fish cage

COURTESY OF N. SIMS

FIGURE 52
An Ocean Drifter cage concept

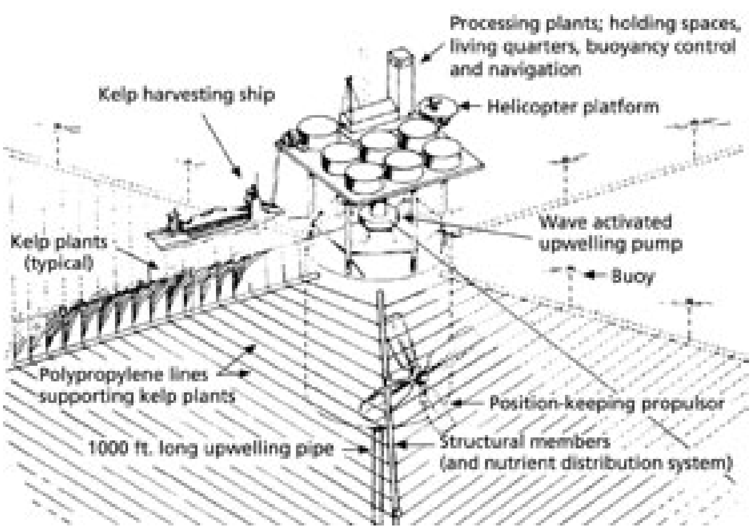


Source: Ryan (2004).

Another kind of ocean farming system was envisioned by Wilcox (1982). This was an untethered powered structure for kelp farming ultimately providing food for human consumption as well as industrial products (Figure 53). The concept is based on nutrient-rich waters pumped up from depths of from 100–300 m with fish and oyster farming also undertaken. A siting criterion was in consideration of latitudes with the least storms. In a techno-economic feasibility analysis of offshore seaweed farming for bioenergy and biobased products, Roesijadi *et al.* (2008) envisioned a 1 km^2 offshore seaweed farm that would be dynamically positioned both vertically and horizontally, with the latter maintaining the system in waters with sufficient nutrients and the former providing protection from storms. For Ocean Drifter and other mobile open ocean farms, a possible limiting factor could be special legal and commercial agreements among nations (Wilcox, 1982) covering not only revenue for use of ocean space, but also animal health, invasive species and the like if the mobile installations traverse EEZ boundaries.

Thus far, the discussion has dealt only with offshore potential with respect to technical and cost-distance limitations. It now turns to a final line of supporting evidence for large offshore mariculture potential that is based on the results of integrating fish and mussel growth-temperature thresholds with technical and cost-effective area for development criteria. The results of this integration indicate that there is much potential for species with grow-out temperature and current speed thresholds similar to those of the three species used in this study. Offshore potential remains large for species like these in absolute terms, both in area and in number of nations that could be participants in its realization even when the cost-effective limit of suitable areas within 25 nm (46.3 km) of a port is imposed (Figures 45 and 46). However, offshore potential is much greater in tropical and warm temperate waters than in cool and cold temperate areas, as indicated by the results for cobia. In contrast to the cobia, the offshore mariculture potential for Atlantic salmon and blue mussel is essentially limited to the nations already culturing these species inshore; however, even though the areas with potential are small in comparison with the cobia, the absolute amounts of area offer much opportunity for expansion offshore (Figures 45 and 46). The apparent advantage of tropical and subtropical waters for the development of offshore mariculture is due not only to temperatures favouring grow-out but also to larger areas meeting technical and cost-effective distance criteria. Olsen *et al.* (forthcoming) showed that the Intertropical Convergence Zone (ITCZ) ranked first area-wise in depths suitable for cages and longlines and for current speed when considered individually and when integrated. In cost-effective area for offshore development, the Northern Temperate Zone ranked first and ITCZ ranked second among mariculture nations, but among non-mariculture nations, the ITCZ ranked first. Finally, when depth, current speed and cost-effective area criteria were integrated, the ITCZ ranked first both among mariculture and non-mariculture nations alike.

FIGURE 53
Conceptual design of a 400-ha ocean food and energy farm unit



Source: Wilcox (1982).

Indicative offshore mariculture potential in terms of surface area for representative fish and a mussel has been shown to be large. A fundamental question is, How much area is sufficient for offshore mariculture development that would contribute to the global food supply? Kapetsky and Aguilar-Manjarrez (2010) used their estimates of area-wise potential for Atlantic salmon and blue mussel in the eastern EEZs of the United States of America, along with production per unit area data for large submersible sea cages (9 900 tonnes/km^2) and mussel longlines (4 000 tonnes/km^2) tabulated by Nash (2004), to estimate total production if only a fraction of the area with potential were to be utilized for offshore mariculture. The same approach is used herein. It is based on the global area with offshore potential for cobia, Atlantic salmon and blue mussel, including meeting the temperature thresholds, cage and longline depths and current speeds, and within the cost-effective area for development. Scenarios of 5 and 1 percent of the area suitable for development for offshore mariculture for each species are set out in Table 15. The extrapolated results are that with the 5 percent development scenario about 49 million tonnes of fish could be produced and about 1.1 million tonnes of mussels. With the 1 percent development scenario, the corresponding production is nearly 10 million tonnes of fish and 230 000 tonnes of mussels (Table 15). In comparison, the mariculture production of fish in 2010 was about 3.3 million tonnes and about 1.8 million tonnes of mussels The amount of space that was allowed to satisfy carrying capacity requirements is not clear from Nash's (op. cit.) tabulations, but space for operational access was included. Harvest in the second year was foreseen. Thus, with grow-out periods of more than one year the actual area required could be somewhat larger to produce the amounts shown on an annual basis in Table 15 especially for Atlantic salmon because of its longer grow-out period compared to the other two species. Nevertheless, an important point made by Nash (2004), and also evident from the results herein, is that production from relatively small areas can have a substantial impact on overall mariculture production.

TABLE 15

Extrapolated annual production from the aggregate areas suitable for the offshore mariculture of cobia, Atlantic salmon and blue mussel with 5 percent and 1 percent of the areas developed for offshore mariculture

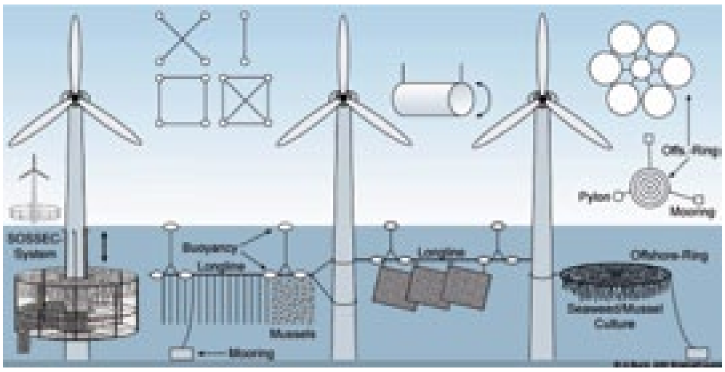
Species	Assumed production rate* (tonnes/km^2)	Total area suitable for development (km^2)	5% developed		1% developed	
			Area (km^2)	Production (tonnes)	Area (km^2)	Production (tonnes)
Cobia	9 900	97 192	4 860	48 110 040	972	9 622 008
Atlantic salmon	9 900	2 447	122	1 211 265	24	242 253
Blue mussel	4 000	5 848	292	1 169 600	58	233 920
Total		**105 487**	**5 274**	**50 490 905**	**1 055**	**10 098 181**

**Nash (2004).*

As a comparison of outputs, Wilcox (1982) foresaw an annual production of 700 000–800 000 tonnes wet weight of seaweeds per square kilometre on ocean farm structures based on artificial upwelling, and that would also include fish and oyster outputs (Figure 53). Forster (2011b; forthcoming) notes that while extrapolations can be pushed too far, based on the kelp (*Laminaria*) production being realized in the People's Republic of China, 1 940 tonnes dry weight/km^2 (Chen *et al.*, 2007), it would need less than 1 percent of the Earth's ocean surface, about 3.1 million km^2, to grow an amount of seaweed equal to all the food plants farmed on land.

Basic kinds of offshore mariculture potential have been identified in this study, including technical, economic and growth of cultured organisms. An important question going beyond the area required for development is the time frame in which offshore potential can be realized. As noted above, the offshore potential that could begin to be tapped in the near future is best described by that identified within the cost-effective area of development as a first approximation. For as long as offshore installations require frequent visits for maintenance, monitoring and harvest, they will have to remain proximate to onshore service installations located in industrial ports or in lesser harbours. Taking advantage of structures established for other uses of marine space, such as oil and gas platforms and wind farms (Figure 54), could accelerate offshore mariculture development by cost-sharing (e.g. shared transportation), as well as allowing mariculture systems to populate areas further offshore by making structures and services multifunctional (Buck, 2011). This would allow some of the present onshore services required of mariculture to be moved offshore (feed warehouses, lodging for maintenance and monitoring staff). One example of a synergistic relationship is shellfish harvesting as a biofouling control on platforms in the Santa Barbara Channel, California, United States of America (Richards, Culver and Fusaro, 2009). There, biofouling was a costly stress-load problem on platform legs and crossbeams that was reduced or eliminated by commercial harvest by shellfish entrepreneurs. One important factor was favourable conditions for the rapid growth of mussels, *Mytilus galloprovincialis* and *M. californianus.* From the viewpoint of sustaining bivalve culture at offshore wind-farm sites, Linley *et al.* (2007) predict with reasonable confidence that blue mussels could grow well at 15 wind-farm locations in three areas of the coasts of England and Wales. According to Brenner (2009) with regard to macroparasites, growth and aesthetical appearance *M. edulis* of high quality can be produced offshore in the German Bight.

FIGURE 54
Offshore wind farm combined with oyster and mussel farming



Source: Buck (2011).

Up to this point, vast offshore mariculture potential has been assumed with other uses of marine space set aside. However, MPAs are an illustration of possible competing, conflicting or complementary uses (Section 4.4) and a reminder that, although the area-wise and nation-wise potential indicated by the results is large, that potential will be reduced considerably by alternative uses for the same marine space, especially in nearshore areas where current marine activities are focused. For an example, in the current study, a hypothetical loss of cobia offshore mariculture potential amounting to about 6 percent in order to avoid MPAs was illustrated. As comparison at the subnational level, reduction in area with offshore mariculture potential when multiple constraints are considered comes from the Gulf of Mexico Aquaculture Fishery Management Plan. One of the alternatives of the plan would establish 13 marine aquaculture zones for fish in cages, amounting to about 5 percent of the Gulf of Mexico EEZ area of the United States of America (Gulf of Mexico Fishery Management Council and National Marine Fisheries Service, 2009; Rester, 2009). The aquaculture zones were defined by depths of 25 to 100 m and current speeds > 10 cm/s. Areas not considered suitable for aquaculture included navigational fairways, lightering zones, oil platform safety zones, permitted artificial reef areas, Habitat Areas of Particular Concern, coral areas, marine reserves, MPAs, areas of high shrimp fishing effort, and hypoxic areas (< 2 mg/l). Consideration of all of these constraints reduced the original area deemed suitable to 36 percent of the original total.

In summary, there are many other uses for ocean space that will affect offshore mariculture potential of which some are possibly conflicting and competing activities, as illustrated by the Gulf of Mexico study above, or potentially complementary (e.g. wind-power installations). An important goal of spatial analysis is to locate and quantify the complementary uses while avoiding or minimizing the competing and conflicting uses (FAO/Regional Commission for Fisheries, 2011). In this regard, this study, in a very broad way, serves to establish the spatial domains that could become offshore mariculture uses as a component in marine spatial planning.

6.5 Future directions

Taking into account the trend for the increased kinds and higher resolutions of environmental variables important for offshore mariculture development as well as improved computing power, it is likely that a grid-cell based model would be better suited to estimating offshore mariculture potential than raster-vector combination used for this technical paper. In this regard, the first step has been taken towards such an alternative approach to estimating mariculture potential that eventually could become a spatially comprehensive grid-cell based model to estimate mariculture development potential at individual locations of relatively small size (see Ferreira, 2013 in Annex 2). Attention was called by Kapetsky and Aguilar-Manjarrez (2013) to the need for applications that include carrying capacity as one of their components or outputs. Applications are needed that incorporate multiple models (e.g. economics, environment, social outcomes), multiple species, and the possibility that they could be scaled up to contribute to geographically broad studies at national levels as a part of a process of estimating aquaculture potential. AkvaVis (Ervik *et al.*, 2008, forthcoming; described by Ferreira *et al.*, 2012) is an "all-in-one" Web-based interactive decision-support system, including site selection, carrying capacity and management monitoring modules, that appears to have much promise for adaptation to estimating offshore mariculture potential at national levels and for the management of its development.

Data from satellite remote sensing were indispensable for the analyses carried out in this study, and will be important for the integration of spatial analyses and modelling referred to above. As stated by Dean and Salim (Annex 3), satellites enable a unique synoptic view of the seas and oceans and regular repeated observations of the entire globe and specific regions that complement and extend data available from operational meteorological and in situ sensors.[6] Operational oceanography data and information products derived wholly or partly from remote sensing include temperature, primary productivity, ocean winds, currents and waves. An important application of such data in real-time is for operational management of mariculture. In contrast to data for real-time management, the build-up of long-time series of data and advances in data processing mean that series of daily, weekly, monthly, annual and seasonal "climatology" data are now readily available at increasingly higher resolutions. In turn, these data improvements will enable more reliable estimates of mariculture potential at all levels while cutting costs. In addition, emerging remote sensing capabilities, such as more reliable identification and tracking of harmful algal blooms, will provide improved spatial and temporal risk assessment. This will complement the methodological approaches developed herein that are meant to stimulate estimates of mariculture potential at regional, national and subnational levels.

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[6] Remote sensing and its integration with GIS to enable spatial analyses for aquaculture and fisheries is covered by Dean and Populus (2013).

6.6 Recommendations

As FAO moves towards guiding the development of offshore mariculture through its regional fishery bodies and via technical assistance at national levels, assessments will have to be undertaken to determine the regions and countries that are most promising for development. Also, decisions will have to be taken on the appropriate technical interventions required to sustain mariculture. National-level assessments could be undertaken at several levels. For example, the results of this study show that a significant number of maritime nations are not yet practising mariculture, let alone offshore mariculture (Chapter 2). This suggests the need for a proactive approach by FAO and interested maritime nations not yet practising mariculture that would be a broad-based but rapid appraisal as a desk study to determine the reasons for the lack of mariculture development. From a spatial point of view, this technical paper provides one of the inputs by identifying the non-mariculture nations ranking highly in offshore mariculture potential. Other inputs could be taken from the Ocean Health Index (Halpern *et al.*, 2012) already described in Chapter 6.3.

Nations already practising mariculture, but at relatively low intensities, would require more detailed appraisals of their potential for the development of offshore mariculture. One of the recommendations of the FAO workshop report on offshore mariculture (Lovatelli and Aguilar-Manjarrez, forthcoming) is for GIS-based feasibility studies to be conducted on mariculture potential at the national level, including appropriate logistics and infrastructure. In fact, spatial analyses should be included at each stage in this process as an indispensable element of policy and planning in order to provide for a quantitative, comprehensive and comparable view of potential. The manner of organization of the spatial analyses supporting estimates of offshore mariculture potential is important in order to attain the most reliable outcome with the least cost.

A holistic project approach is needed based on an interdisciplinary team that plans the study using the principles of the FAO Code of Conduct for Responsible Fisheries (FAO, 1995; FAO Fisheries Department, 1997) and the EAA (FAO, 2010) as a starting point and with attention to the role of spatial planning tools to contribute to the realization of the EAA (Aguilar-Manjarrez, Kapetsky and Soto, 2010). The project could be placed in a government agency and/or executed by a consulting firm. An important stipulation is that the team should identify its information needs for each discipline at the beginning, and integrate its expertise in an interdisciplinary way thereafter. At the least, the core team should consist of a mariculture expert with a broad knowledge of species and culture systems, an aquaculture economist (modelling), an environmental expert (carrying capacity modelling), a sociologist (societal costs and benefits), and a GIS expert with experience in mariculture, marine fisheries or marine ecosystems. Built into the project should be funds to access additional expertise as required (e.g. marine aquaculture engineers, oceanographers, mariculture practitioners, mariculture entrepreneurs, marine legal experts). Most important is the contact with the mariculture industry in order to ensure that the design of the study is shaped realistically and so that the predictions of potential can be verified with experience from mariculture practice. The team has to be outward looking in order to obtain information and advice from the commercial sector, university researchers, government agencies, and from other potential users and conservers of marine space. Regarding government agencies, it is worthwhile to note that for the foreseeable future offshore mariculture has to be shore based. Thus, local governments and the many stakeholders they represent are important participants in planning for offshore mariculture development. An example of a national-level desk-based appraisal of the opportunity for offshore aquaculture is provided by James and Slaski (2006), but spatial analyses appear to have contributed little to the process. In contrast, an atlas of suitable sites for mariculture projects has been produced by the Sultanate of Oman (Ministry of Fisheries Wealth, 2010) that is based on remote sensing and spatial analysis, but would be considered as a companion piece to a more broad-based study of mariculture potential.

Viewed from a commercial and entrepreneurial standpoint, the results of such analyses can go a long way towards stimulating interest and confidence in offshore mariculture development. The utility and value of estimates of mariculture potential can be increased and the results improved in a number of ways, including by expanding the number of animal species and by adding marine plants and their culture systems, by increasing the numbers of criteria and the resolution of the data, and by applying a model-based approach. All of these refinements can be achieved at a relatively modest cost. Given the experiences gained in this study, efforts should be made to refine the process and to technically assist countries to implement their own estimates of mariculture potential. Based on the result that most of the offshore fish farming potential is in the ITCZ, it can be inferred that many of the nations are in the "developing" category and may require technical assistance. Funding for both of these activities should be included in the broader effort to expand mariculture to offshore.

Looking more broadly, there is a pressing need to identify areas that can help to satisfy the food needs of the increasing world population. Forster (2007) points out that if the oceans are to be farmed like the land, then the offshore areas must be farmed for plants that will provide human food as well as industrial products. This indicates assessing the potential for farming marine macrophytes (seaweeds) on floating structures, or locating or creating conditions for floating seaweeds (Forster op. cit.). This need is being satisfied by a global review currently under way by FAO on seaweed aquaculture, developmental constraints and opportunities. Spatial analysis can be applied to the "What?", "Where?" and "How much?" of offshore seaweed farming potential much in the same way as for the finfish and mussel analysis of this technical paper once environmental, technical and economic thresholds have been established. The results of the seaweed study should then be integrated with those for finfish and shellfish in order to reveal opportunities for IMTA.

Going along with the need to predict offshore mariculture potential is another need that was identified by Knapp (forthcoming). That need is to monitor the growth of the offshore mariculture industry. For this purpose, FAO and Member countries will need to create a new aquaculture statistical category "offshore mariculture". Underlying this initiative is the need for a simple, spatially oriented but unambiguous concept of offshore mariculture. In this regard, and most simply, offshore mariculture from a spatial perspective is defined by where offshore mariculture is presently being practised, by the species that are being cultured, by the culture systems employed, and by the condition of the surrounding environments. The surrounding environments include the biophysical, social and economic environments along with their administrative contexts. Thus, offshore mariculture, present or future, can be defined spatially on maps by the offshore and onshore locations of installations with their attributes catalogued in spatial databases. The combination of the spatial data and attribute information when categorized by administrative, social, economic and ecological criteria could be integrated into an offshore mariculture development and management- information type system. Such an information system would have many applications within the realm of aquaculture (promotion, policy and planning, regulation). More broadly, it would place mariculture in the context of more general development and management of ocean space within marine spatial planning initiatives, such as set out by the FAO/Regional Commission for Fisheries (2011) and in atlas form by Suárez de Vivero (2011).