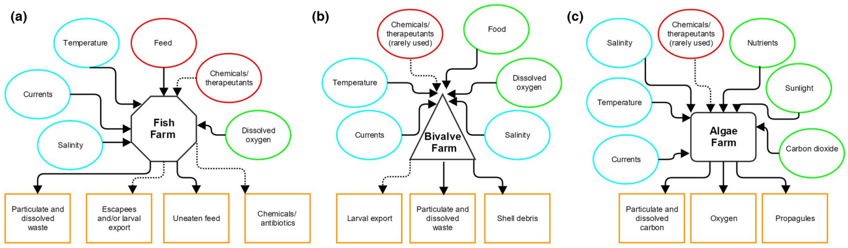
AQS415 PRINCIPLES OF AQUACULTURE ENGINEERING
Week 8. Off-shore aquaculture

Offshore aquaculture: Spatial planning principles for sustainable development



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Schematic of key inputs and outputs associated with the three major categories of aquaculture: (a) fed, (b) unfed, and (c) autotrophic. Red indicates external inputs into the farm; green indicates environmental inputs; blue indicates other environmental conditions that affect the farm; and orange indicates outputs from the farm into the environment. Dashed lines indicate inputs and outputs that are only sometimes present

Offshore aquaculture has been defined using a variety of criteria, including water depth, distance from shore, wave exposure, and jurisdictional boundaries, here, we use a broad definition that includes all mariculture that is located in open water (i.e., not directly adjacent to land or within a bay or fjord). There is significant diversity in marine aquaculture species, with nearly 200 species currently being farmed (FAO 2015) and many more under development; however, all types of mariculture fall into three broad categories: fed (e.g., fish, most crustaceans), unfed (e.g., filter-feeding bivalves, some grazers, and detritivores), and autotrophic species (kelp and other algae). Each of these culture categories interacts with the environment in fundamentally different ways, both in terms of external inputs to the farm and effects of the farm on its surrounding environment. As aquaculture moves into new frontiers—both geographically and technologically—there is an important opportunity to determine where to pursue offshore development in the context of the ocean's complex ecological dynamics and the diversity of existing marine activities and benefits that could interact with or be impacted by aquaculture. We examine four categories of spatial interactions between offshore aquaculture, the environment, and other uses: effects of the environment on farms; effects of farms on the environment; cumulative impacts and regional planning issues; and synergies and conflicts with other ocean management goals.

Effects of the environment on farms

An essential consideration for offshore aquaculture planning is determining which areas could be most productive and profitable. The suitability of locations varies widely, even over small distances. Physical factors, such as water temperature, ocean currents, sunlight, and food and nutrient availability, have a direct effect on the growth of aquaculture species. Unfed and autotrophic aquaculture species are particularly sensitive to environmental conditions because they rely on the surrounding environment to provide the energy needed for growth. Available oceanographic data can be integrated into species-specific growth functions to compare the suitability of potential sites for maximizing growth. There are also several software applications that can model site-level production for specific aquaculture species, such as the FARM model (Ferreira et al., 2007), ShellSim, Depomod (Cromey, Nickell, & Black, 2002), and Aquamodel (Rensel, Kiefer, Forster, Woodruff, & Evans, 2007). While these models are designed for modeling site-specific production and impact, they can also be utilized to determine the areas of highest production within a region by running the model across a spectrum of sites. This type of spatial comparison of productivity has been applied to nearshore bivalve aquaculture in Chile and Scotland (Ferreira et al., 2008; Silva et al., 2011) and to offshore aquaculture in the Southern California Bight (S. Lester, personal communication, 2016). Generally, this type of approach requires significant environmental and farm level data, such as currents, primary productivity, temperature, and stocking density, which can limit its broad application in areas with limited environmental information.

Farm location also impacts the quality of seafood produced. Notably, concerns about the accumulation of toxins in seafood are driving efforts to ensure the safety of aquaculture products (Focardi, Corsi, & Franchi, 2005; Karunasagar, 2008). Existing research on the distribution and impacts of land-based pollutants on marine ecosystems (e.g., Fabricius, 2005; Halpern et al., 2009) and monitoring of water quality could help inform offshore aquaculture planning. For example, Fabricius (2007) detail spatial, physical, and hydrodynamic properties of the environment that are likely to affect the susceptibility of coral reefs to the effects of land-based runoff. Many of the characteristics of susceptible reef areas, such as close proximity to discharge, shallow depths, and slow currents, are also likely to be risk factors for aquaculture operations. In general, moving into offshore environments, which is likely to increase the distance from most pollution sources and to increase water flow, will be beneficial in mitigating food safety concerns. Evidence from bluefin tuna ranching in Australia suggests that moving marine aquaculture into offshore environments may also enhance fish condition, while reducing parasite loads and mortality rates (Kirchhoff, Rough, & Nowak, 2011).

Farm productivity and profit can also be impacted by wild predators, such as seals, sea lions, otters, and birds, that are often attracted to mariculture farms. For example, predator presence near farms can generate stress-related fitness reductions in farmed fish, damage to farms, and increased escapement of farmed fish from damaged nets (Nash, Iwamoto, & Mahnken, 2000). These interactions can be minimized through cage design and auditory or other deterrents (Quick, Middlemas, & Armstrong, 2004), but location of the farm is also important. For example, evidence from both Australia and Chile suggests that predation rates on an aquaculture farm are related to distance from the nearest pinniped colony (Kemper et al., 2003). In general, moving farms further offshore and away from coastal concentrations of marine mammals is likely to help minimize interactions and protect the cultured product from predation (Nash et al., 2000).

Farm location can also have a significant impact on the cost of farm operations. Factors such as depth, distance from port (and associated infrastructure and processing facilities), wave conditions, and storm activity modify transport, labor, construction, and maintenance costs (Kaiser, Snyder, & Yu, 2011; Klinger & Naylor, 2012). Additionally, risks due to climate variability, pollution, disease, and harmful algal blooms can vary spatially (e.g., Husson, Hernández-Fariñas, Le Gendre, Schapira, & Chapelle, 2016) and may have an effect on the profitability of a farm.

2.2 Effects of farms on the environment

By introducing a high density of additional life into the ocean, mariculture affects the surrounding environment in diverse and complex ways. In some cases, this can lead to desirable outcomes; for example, algal aquaculture has the potential to improve water quality in regions that have been affected by nutrient pollution through uptake of nitrogen, phosphorous, and carbon (Neori et al., 2004). Bivalves have also been promoted for their ability to reduce the standing stock of phytoplankton, and therefore potentially mitigate some of the effects of eutrophication (Cranford, Dowd, & Grant, 2003). However, aquaculture can also contribute to nutrient and chemical pollution (Cao et al., 2007). The magnitude of these effects is heavily influenced by operational characteristics, such as the species farmed, stocking density, and feeding strategy, but location also plays an important role. Specifically, physical and chemical characteristics of the surrounding environment, such as background nutrient levels, proximity to sensitive habitats, currents, and depth, help to determine the fate and impact of pollutants released from a farm.

Both fed and unfed aquaculture operations can release particulate organic matter that is likely to fall to the seafloor, potentially leading to local oxygen depletion in and near the benthos as the organic matter is consumed by microbes (Ferreira et al., 2007; Price & Morris, 2013). Generally, deeper water and faster currents result in more diffusion of organic material (Lovatelli et al., 2013; Sarà, Scilipoti, Milazzo, & Modica, 2006). For example, a study examining ten aquaculture sites across Europe found that shallower depths and slower current speeds were significant predictors of higher levels of benthic impact; these hydrodynamic variables were second only to the amount and duration of aquaculture production in predictive strength (Borja et al., 2009). In general, while bivalve farms have been shown to have benthic impacts in shallow sheltered areas, there are low risks of significant organic enrichment in well-managed marine farms, especially in areas of high current and depth (typical of offshore sites) (Crawford, 2003; Crawford, Macleod, & Mitchell, 2003). The potential benthic impacts of offshore finfish farming are less clear, and can vary significantly with farm practices (such as stocking density) and site characteristics (Price & Morris, 2013). While high levels of nutrient enrichment can cause adverse hypoxic conditions, low levels of nutrient enrichment may only have a minor effect and can actually result in an increase in benthic diversity (Rosenberg, Agrenius, Hellman, Nilsson, & Norling, 2002).

One possible approach to mitigate pollution from finfish farms is through integrated multitrophic aquaculture (IMTA), which aims to imitate natural ecological nutrient cycling by pairing different trophic levels of aquaculture in the same area (Neori et al., 2004; Troell et al., 2009). Fed aquaculture produces excess organic matter, which can feed bivalve aquaculture both directly and indirectly (i.e., by encouraging additional phytoplankton growth). In addition, fish and bivalves also produce dissolved nutrients that are necessary, and often limiting, for the growth of autotrophs. Therefore, placing unfed and autotrophic aquaculture in the same location as or adjacent to fed aquaculture could theoretically improve growing conditions for bivalves and kelp while mitigating some of the potential impacts of fed aquaculture. However, commercial operationalization of this idea in the offshore environment is relatively new and faces challenges with efficiency and economic scaling (Troell et al., 2009). The potential effectiveness of IMTA depends on environmental context, particularly background nutrient levels, food availability, and hydrodynamics (Troell et al., 2009).

Another environmental concern associated with offshore aquaculture is potential negative interactions with marine mammals, birds, and other wildlife. Wildlife can be attracted to aquaculture farms and then get caught in lines and nets (Kemper et al., 2003). However, the frequency of entanglement is typically quite low, and in general, the risk of entanglement in aquaculture gear is less than the risks associated with fishing gear (Young, 2015). Conversely, there is also concern that farms may displace whales and dolphins, which could impact their access to foraging grounds or impede movement. Evidence from Western Australia supports this concern by demonstrating that bottlenose dolphins avoid oyster farming areas (Watson-Capps & Mann, 2005). Information about home ranges, movements, and behaviors of local marine mammals in response to aquaculture farming can help inform aquaculture development and provide better understanding of the risks to wildlife.

2.3 Cumulative impacts and regional planning issues

As the density of aquaculture within an area increases, additional regional-scale considerations emerge regarding the number of farms that can be supported as part of a healthy ecosystem. These considerations are quite different and conceptually almost opposite for fed and unfed aquaculture: cumulative effects of adding additional organic matter to the ecosystem for fed aquaculture vs. cumulative effects of organic removals from the system for unfed aquaculture.

For offshore finfish farms, there is considerable uncertainty about how pollution impacts scale with the concentration of farms, and at what density and in what environments eutrophication is likely to become significant (Cao et al., 2007; Klinger & Naylor, 2012). Much of what we know about nutrient enrichment from mariculture comes from studies of farms in sheltered coastal locations (e.g., McKinnon et al., 2010; Niklitschek, Soto, Lafon, Molinet, & Toledo, 2013), where limited water flow can amplify pollution problems. Since offshore sites tend to be less susceptible to nutrient enrichment due to increased water flow and depth, offshore locations should sustainably support a higher density of production than sheltered nearshore locations, particularly if conservative stocking densities are used. Nonetheless, both the environmental context, in terms of background nutrient concentrations, other sources of organic influx, and the strength of currents, as well as farm management, particularly stocking density and feeding practices, are important in determining whether larger scale nutrient enrichment is likely to be a concern in any given area. If cumulative pollution is considered a risk, aquaculture-specific modeling software, such as Aquamodel (Rensel et al., 2007), can provide further insight on the potential for cumulative nutrient pollution issues by modeling the effluent from several farms within a region.

With unfed, specifically bivalve, aquaculture there is a farm density at which the cultured species will consume so much food from the water column that ecosystem function will be impacted. Potential impacts include reduced wild recruitment due to over consumption of planktonic larvae and reduced food availability for wild populations (Gibbs, 2004). Several studies, including by Jiang and Gibbs (2005) in New Zealand and by Byron, Link, Costa-Pierce, and Bengtson (2011) in Rhode Island, have used Ecopath, an ecosystem modeling software, to assess both the effect of existing bivalve culture on the ecosystem and determine sustainable limits to future production. While this type of study is data intensive, it is a powerful approach for considering ecosystem-level effects and providing an assessment of carrying capacity. In general, food competition between wild and farmed species is more likely to be a concern in regions with low primary productivity (Gibbs, 2004; Grant et al., 2007), although those regions are also less likely to experience intense development of unfed aquaculture. In addition, the high water flow typical of open-ocean farms makes significant issues with food competition unlikely, except at very high farm densities. Similarly, local nutrient depletion is potentially possible in areas of very-high-density kelp culture, but this has not generally been an issue in kelp-growing regions (Kraan, 2013).

The risk of disease outbreak is also a prominent concern with aquaculture development, particularly in terms of cumulative impacts from multiple farms in a region (Holmer, 2010; Leung & Bates, 2013). Although site selection is often seen as secondary to management and husbandry practices in reducing disease outbreaks, the spatial distribution of aquaculture farms can play an important role in modifying this risk (Murray & Gubbins, 2016; Salama & Murray, 2011). The diversity of potential diseases and the constant emergence of new disease threats make spatial planning to reduce disease risk challenging (Lafferty et al., 2015). Each disease is specific in terms of its biology, how far it is likely to spread, and the specificity of its targeted host. Host specificity is particularly important in determining whether any disease outbreak is a serious environmental concern that has potential to spread to wild populations or is likely to remain within aquaculture farms (and is primarily an economic issue). Unfortunately, there are still significant unknowns concerning the biology and spread of many emerging diseases that could affect aquaculture species. However, even without disease-specific information, spatial planning can reduce disease risk. For example, reducing the size and density of farms and increasing the distance between farms can mitigate the risk of disease spread; generally, larger farms spaced further apart pose less risk than multiple smaller farms clustered closely together (Salama & Murray, 2011). Infectious salmon anemia (ISA) is one disease that has received considerable research attention due to its history of impact on the aquaculture industry. Researchers in Chile and Norway have found that ISA spread among farms is more likely when farms are clustered closely together and recommend a separation distance of at least five kilometers between farms (Jarp & Karlsen, 1997; Mardones, Perez, & Carpenter, 2009). These simple guidelines are especially useful for diseases that are not shared with wild stocks and could be refined considerably with specific information about both the environment and the disease of concern.

Importantly, it is not precisely the geographic proximity of farms that matters for disease spread, but rather their connectivity—in other words, the likelihood that infectious agents from one farm reach another farm. In addition to physical distance, current speed, and direction also determine site connectivity. Oceanographic models, such as Regional Ocean

Modeling Systems (ROMS) (e.g., Dong, Idica, & McWilliams, 2009), can be used to evaluate connectivity by modeling the release of particles at any one location and tracing the likelihood of transport to all other locations (Simons, Siegel, & Brown, 2013). Indeed, a recent study demonstrated that water contact via current flow had the strongest explanatory power in describing the dynamics of pancreas disease spread between salmon farms in Norway (Stene, Viljugrein, Yndestad, Tavornpanich, & Skjerve, 2014). This approach can be useful for forecasting the risks of disease spread (Groner et al., 2016) and informing spatial planning to minimize the connectivity between aquaculture locations. Spatial risk assessment for disease spread can be combined with other models to assess overall production and ecological carrying capacity for a region (Ferreira, Saurel, Lencart e Silva, Nunes, & Vazquez, 2014). This approach also has the advantage of using a systems perspective to demonstrate how the location and density of farm development affects both other farms and the surrounding environment across a spectrum of scales and sustainability metrics.

In addition to minimizing connectivity among farms, locating farms away from dense or vulnerable wild populations may reduce the risk of disease exchange between wild stocks and farmed animals (Holmer, 2010). Wild populations are well documented as the source of most aquaculture diseases (via water exchange, feed, or broodstock), and even diseases that do not affect wild hosts can be problematic if transferred to an aquaculture setting (Lafferty et al., 2015). However, it is the risk of disease export from aquaculture to the wild that has created the most concern and controversy from an ecological perspective (Johansen et al., 2011). This risk may be heightened when the farmed species is native or related to a native species (Gross, 1998). While diseases do pose potentially severe risks to wild populations, the role of aquaculture as a source of these diseases is controversial, and considerable uncertainty around the dynamics of disease spread from farms to wild stocks remains (Lafferty et al., 2015).