Article

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Toward a Theology of Sustainable Aquaculture: Wisely Producing Safe Abundant Seafood While Enhancing Fruitfulness of Aquatic Creatures

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Aquaculture, commonly conceived as "fish farming," includes the culture of animals, plants, or other species in water. Although about 70% of Earth's surface is covered by water, aquaculture often uses much smaller spaces such as tanks, ponds, raceways, or aquatic enclosures to grow aquatic food, fiber, and other resources. Theologically, humans are called to "protect and serve" (Gen. 2:15), and throughout the Bible, there are calls to good stewardship and cultivation while allowing for fruitfulness of other creatures. Biblically, fish are seen as God-created aquatic creatures, often used as food, with implications for wise stewardship (e.g., Psalm 8).

At the present, many fisheries around the world are overfished. Sustainable aquaculture should address environmental, economic, and health concerns, and it could help reduce the stress on natural fisheries. As the fastest-growing protein sector, aquaculture now produces more seafood than the wild harvest of all the world's oceans (now approximately 120 million metric tons per year). This promising and expanding field (approximately 6–8% growth per year over the last 50 years) includes extremely efficient converters of protein, micro- and macro-algae (seaweeds) that can absorb unwanted wastes and clean the water, and filter feeders such as oysters and clams that clear the water of algae and other particles, simultaneously contributing various ecosystem services and habitat. Ongoing problems include pathogenic and related disease issues, environmental pollution in surface waters, food safety, increasing automation utilization, potential genetic concerns, and the relatively recent start of modern aquaculture (most aquaculture growth has occurred since 1970). This article addresses each of these hurdles, identifies areas of theological and ethical concern, and clarifies matters of interest to Christians and others, suggesting possible ways forward in this fast-growing but challenging field.

Keywords: aquaculture, automation, food safety, seafood, water quality, ethics, theology, sustainability

"And God said, 'Let the water teem with living creatures … so God created the great creatures of the sea and every living thing with which the water teems and that moves about in it.'" (Gen. 1:20–21, NIV)

"Then God said, 'Let us make mankind in our image, in our likeness, so that they may rule over the fish in the sea …'" (Gen. 1:26a)

"The Lord God took A'dam *(earthling) and put him in the Garden of Eden to* shmar *(protect) and* abad *(serve) the garden." (Gen. 2:15)*

"Lord our Lord, how majestic is Your name in all the earth ... You care for (human beings) … You have made them rulers over the fish in the sea, all that swim the paths of the sea …" (Ps. 8:1,6–8)

"Taking the five loaves and two fish and looking up to heaven, Jesus gave thanks and broke them. Then he gave them to the disciples, and the disciples gave them to the people. They all ate and were satisfied." (Matt. 14:19b–20a)

Definition of Sustainable Aquaculture

Aquaculture is the culture of aquatic organisms for food, fiber, and other resources.[1] It has developed quickly in recent decades, producing only a few percent of total fish consumed in 1970, but now providing roughly as much biomass as wild harvest from all the world's oceans (albeit in a much smaller total area) and is worth roughly $160 billion.[2] Fish and shellfish currently represent over 17% of all animal protein consumed globally, providing high quality protein for the growing middle class as well as low cost protein for the world's poor.[3] It is also the fastest-growing modern protein source on the globe.[4] There is evidence of historic culture of carp in China, of floating plant/fish systems in Mexico, of historic fish ponds in Europe, and of indigenous farming of fish from coastal embayments in historic Hawaii, among others.[5] These systems appear to have been relatively small and fairly sustainable. However, concerns about sustainability of modern aquaculture for large populations raise questions on how to minimize adverse effects on the environment, enhance production efficiency, and optimize health;[6] each of these may be considered for their ethical and theological implications.

A truly sustainable aquaculture would minimize environmental effects and provide safe, ethical, and healthy products while utilizing the ability of finfish to convert feed very effectively, ideally allowing wild fish stocks to recover from their currently depleted status. Modern aquaculture is only a few decades old (see fig. 1) but is likely to continue to grow, so we explore a theology of sustainable aquaculture.

Seafood includes finfish, crustaceans, fish eggs, marine mammals, mollusks, aquatic plants, and algae. Consumer demand for seafood has increased due to its perceived health benefits and abundance.[7] With global fish production (wild caught plus aquaculture raised) now approaching 170 million metric tons, and with seafood making up 17 percent of all animal protein consumed by the global population (in 2020), seafood safety and sustainability is critical.[8]

A report by the Food and Agriculture Organization of the United Nations (FAO) indicates that Americans now eat about 16.5 pounds of seafood per year compared to the 10 pounds consumed in the 1980s.[9] Aquaculture, in particular, is rapidly increasing production, while capture fishing has remained stagnant.[10] Although aquacultural systems do rely on significant capital and energy, it has been noted that the edible meat yield in fish is usually high compared to livestock, both in terms of feed conversion ratio and meat yield per total animal weight.[11] Despite the productivity and growth of aquaculture, obstacles remain and must be addressed to move toward sustainability. Some of the most important questions have ethical or theological aspects: How can we provide for fruitfulness of both humans and other creatures? How can we care for God's good creation, including aquatic creatures and environments?

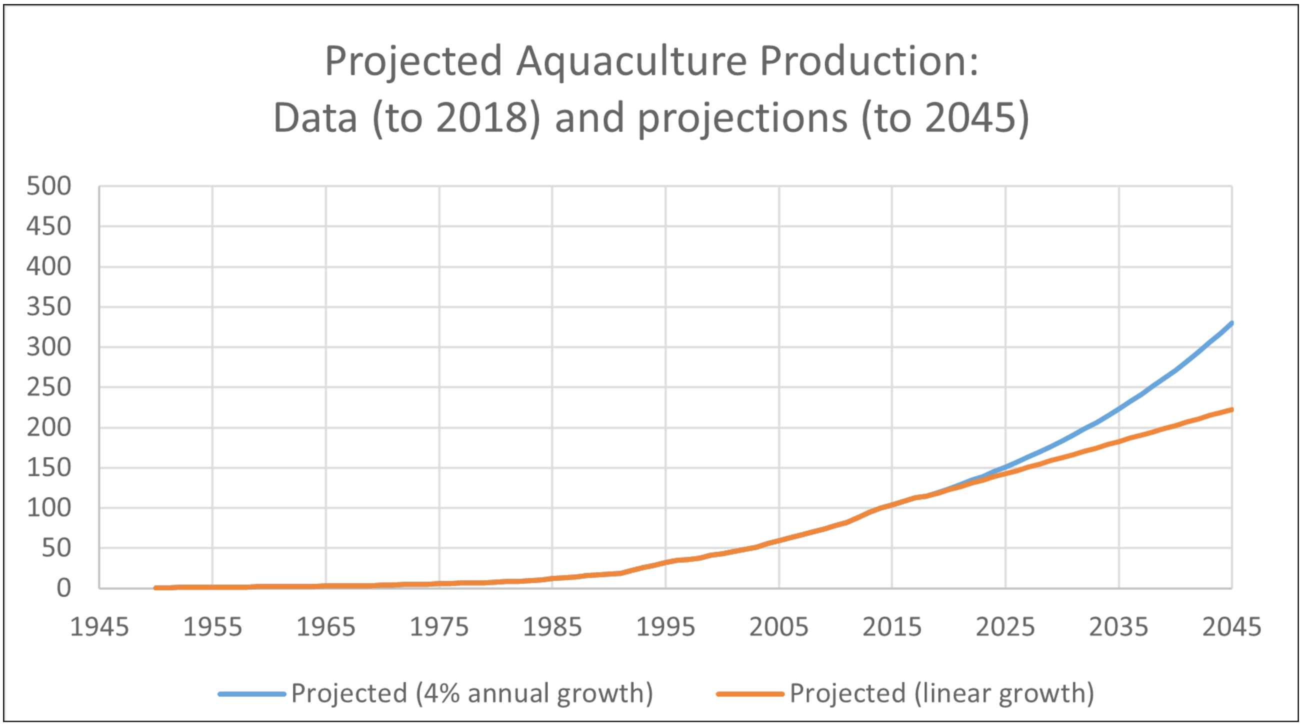


Figure 1. Growth of aquaculture has now surpassed all wild caught seafood (based on data from FAO 2020). About 40% of aquatic production is macroalgae or seaweed. The long-term growth has been 6–8% per annum for several decades. Units are millions of metric tons (MMT) of annual production.

Harmful Results of Aquaculture

Thirty percent of regional fish stocks are over-exploited, and a majority of fisheries are at or beyond their sustainable limit.[12] The ramifications of over-fishing on global fisheries include coastal pollution, diseases, genetic introgression, and human and animal health.[13] Recent work argues that the world's oceans have been substantially affected and that aquaculture has not yet provided enough fish to reduce the stress on the world's natural fisheries.[14] However, without continued growth of aquaculture to feed growing populations, can we hope to provide protein for millions of poor or hope for the world's depleted fisheries to be restored?[15] Conversely, can the growth of aquaculture continue, and if so, at what cost?[16] How might we move aquaculture onto a more sustainable path, providing high quality protein for today while stewarding our oceanic and freshwater resources for the future?[17] What special contributions and considerations come from a theological perspective? These questions are central to providing a vision for future development of aquaculture that not only protects the oceans but ideally also contributes to restoring marine fisheries and other aquatic habitats while providing healthy, efficient protein for the world.

Implications of Aquaculture on Wild Stocks

While the hope has been that aquaculture might reduce the stress on wild stocks, at least two major areas remain as significant considerations. First, carnivorous fish cultured in tanks or cages still require a high-protein diet, and fish meal is part of that diet. This fish meal often comes from wild bycatch and drives up demand for wild caught fish. Parallel to this is another large and growing field: the demand for fish in animal diets, including pets. Cats in particular need protein in the diet, and fish is often considered a desirable part of cat diets. Finally, the "farming" of some fish such as tuna is often dependent upon catching wild fish and then fattening them in ocean cages.[18] This is yet one more demand on wild stocks.

How can we reduce these outcomes? Johann Bell and coauthors suggested ways to sustain Pacific Island economies which are dependent on tuna harvest.[19] Others have addressed ways to advance tuna culture, but at the same time reduce adverse effects on wild stocks by breeding and culturing tuna in captivity.[20] These efforts require more work before they will be useful in solving the concurrent problems of the wild fisheries.

Another example of aquaculture's influence on wild fish stocks has involved the farming of Atlantic salmon from Norwegian stock. These fish have escaped at times and interbred with the local populations (typically relatively small in eastern Canada and the US); the resulting hybridization between farmed and wild stocks, and genetic changes in the overall wild population, are causes for concern. As recently as 2018, substantial occurrences of "large escapes" of domesticated Atlantic salmon "unambiguously" diminished populations in seventeen of eighteen rivers sampled.[21] These circumstances are limiting the fruitfulness of wild fish (contrary to Genesis 1) and damaging the environment. Dis-covering methods to mitigate the effects on wild stocks is crucial for advancing toward a more sustainable aquaculture.

Pollution, Wasted Resources, and Environmental Impacts

The presence of excess nutrients both from land-based human farming and industry and also from aquaculture in and near coastal areas has been documented in various "dead zones" and related phenomena. Some of this is directly attributed to excess feed and feces from aquaculture farms. Growth may exacerbate this, but more-sustainable practices (in the case of seaweed and filter feeders like oysters) might improve water quality. However, at present, numerous studies have noted ongoing pollution in areas near and often several hundred meters from aquaculture feeding operations.[22] Clearly, as aquaculture grows, these consequences will escalate unless efforts are made to minimize feeding operations or to manage them differently. Michael Timmons and Brian Vinci suggest recirculating aquaculture systems (RAS) with fish tank culture to manage wastes more effectively.[23]

Atlantic Sapphire, whose website boasts an entire section on sustainability, grows oceanic fish including Atlantic Salmon in recirculating systems "better for fish, for people and for the planet we all share," and claims to "skip the fish wastes, escapees, hormones, parasites, and antibiotics used in some sea-based fish farming."[24] These are fairly idealistic claims which do not acknowledge the significant capital and operating costs of most land-based RAS or other complexities that may be posed in these more controlled environments. While technology may be deployed to sustain or harm, sustainable activities must consider the laws of physics and biology and work with them, not against them. We also have the task of maintaining humility, a fundamentally theological approach. At the core of a theology of sustainable aquaculture lies the balance between biology and ecology.

Ecosystems can also be affected by aquaculture. For some time, mangrove ecosystems were destroyed for shrimp farming, leading to loss of protection from tsunamis and coastal storms.[25] More recently, Rosamond Naylor et al., in 2021, note that "destructive habitat conversion, particularly by shrimp farming in mangrove ecosystems raised in the previous review has declined markedly since 2000" and cite studies from China and Vietnam.[26] However, they also note that ongoing serious consequences include "pathogens, parasites and pests," as well as environmental pollution which may lead to harmful algal blooms and may be exacerbated by changes in climate. These problems at the ecosystem level may be further exacerbated by biological limitations of aquaculture.

Biological Problems: Genetic Introgression, Diseases, and Invasive Species

Escapees from cage-based ocean aquaculture systems (or pond systems during flood events) can contribute to genetic introgression, genetic changes from cultured fish that may reduce survival, and genetic diversity of wild stocks. Diseases can be transmitted and may develop more quickly in high-density fish farms, either in the ocean or in tanks or ponds. Parasites may grow on fish; in ocean cages, they can be transmitted to wild animals nearby. Sea lice (parasites found on salmon) have been documented to infest wild fish in the vicinity of cage-based fish farms, posing a problem costing over $100 million annually. Similar dilemmas are encountered in land-based farming, and they significantly influence the potential sustainability in the aquaculture sector. Furthermore, they tend to be inflated as operations grow.

This article is not the first to tackle topics concerning sustainability or even theology and sustainability. In fact, the literature on both sustainable agriculture and sustainability in aquaculture (the culture of food, fuel, and fiber in aquatic environments) has grown in recent decades. Rex Caffey addressed sustainability in modern aquaculture just over two decades ago.[27] Since that time, there has been much scientific work and possibly even more popular activism both for and against aquaculture and its sustainability.[28] The genetics of aquatic systems, introduced species, and disease proliferation within and beyond high-density aquaculture systems are some aspects requiring future research and attention.

The genetic understanding of aquaculture species, compared to other forms of agriculture, is relatively nascent. For example, several species of animals were cultivated (and genetically selected) in biblical times, so we are likely thousands of generations into these genetic selection processes. Most aquaculture species are, at most, a few decades removed from the wild. For example, modern catfish (a $400 million per year industry in the southeastern United States) have been genetically managed for perhaps twenty generations, while striped bass are only on generation eight.[29] Compared to land-based agriculture, aquaculture is very early in its development, but this also allows consideration of how to wisely manage genetic and biological resources.

To date, there has been limited genetic engineering in aquaculture. There has been modest work on triploid (sterile) oysters and tilapia, but this does not introduce any other species' DNA into either oysters or tilapia. One exception is the AquAdvantage salmon (with inserted genetics from other species), which has been viewed positively as a "pioneering application of biotechnology in aquaculture"[30] and negatively with concerns that parallel those about genetically modified organisms (GMOs) in land-based plants and animals. GMOs have now entered the pet trade, including "GloFish." On land, many of our cultivated plant species are now genetically modified (e.g., corn is now over 90% GMO across the United States), whereas this has not yet happened as extensively in aquaculture. Serious concerns include growth hormones and "playing God," unknown consequences of these techniques on the environment, and food safety. In 2015, the FDA approved the AquAdvantage salmon and declared it safe to eat.

Whether and when other species may be introduced is not clear. There has been significant resistance to GMOs.

Furthermore, concerns regarding invasiveness arise with the introduction of an entire species. Invasive species may be presented unintentionally in new habitats where there are few predators to keep them in check. Introduced species (aquatic species native to one area, introduced to another) are common. For example, Atlantic salmon (non-GMO) are grown on the west coast of the United States (US) and Canada, as well as Norway and Chile. Washington state raises five different cultivated species of oysters: the majority are native to other regions, including the Atlantic Eastern oyster *Crassostrea virginica* and the Pacific oyster *Crassostrea gigas,* native to the western Pacific. So far, it appears that these species have not displaced native species excessively, but there are well-founded concerns.

The nutria, or swamp rat, *Myocastor coypus*, was introduced to the Gulf coast from South America to cultivate for fur, but it escaped and has done considerable damage to coastal wetlands. Attempts to control this invasive pest have included paying bounties for trapping, turning them into dogfood and sausage, and reinvigorating the native predator *Alligator mississippiensis* population.

Another example of invasive finfish species is the jumping carp or silver carp, *Hypophthalmichthys molitrix*, slowly invading the US Midwest. Ironically, it is threatened in its native China and Siberia.[31] One solution would be to utilize native species to compete with invasive counterparts. A second approach would be to include biosecurity techniques to reduce the spread of invasive species. These are concerns that must be addressed as aquaculture expands.

Health and Safety

Animal and human health are both concerns. Fish is generally acknowledged as high-quality protein, but questions about health of fish may be tied to pathogens. Biosecurity can help, but it is acknowledged that a mix of practices can be found worldwide.[32] Human health concerns with wild caught finfish include substances that may be bioaccumulated such as mercury and other heavy metals. Generally, cultured seafood should minimize this risk, as feed is controlled and bioaccumulation is minimized in cultured systems, where feed conversion is very efficient.

While filter feeders such as oysters, clams, and mussels help clean the water and algae can extract nutrients from the water, food safety in raw seafood is still a concern to safely enjoying these products. We see in the scriptures that eating animals and using agriculture for food has always been an integral part of humanity's function on Earth. In Leviticus 11, God invites the Israelites to consume aquatic animals with fins and scales. At that time, however, shellfish and other sea creatures were regarded as unclean.

After the death and resurrection of Jesus Christ came the introduction of a new covenant between God and those who obey him. A result of this new covenant was the inclusion of Gentile believers in the family of God. This is demonstrated in Acts 10 when God spoke to Peter through a vision. God placed before Peter animals that were previously viewed by Jews as unclean and told him to kill and eat them. Peter refused, but God told him, *"Do not call anything impure that God has made clean"* (Acts 10:15). While God used this vision to call Peter to share the good news of the gospel with non-Jews, a dual meaning regarding a change in food consumption can be understood from the text. Paul explains this new freedom in his letter to the Corinthians. He urged them to realize that *"… food does not bring us near to God; we are no worse if we do not eat, and no better if we do"* (1 Cor. 8:8). However, Paul urges the believers not to be stumbling blocks to brothers and sisters who feel that eating certain foods is sinful. He said, *"Therefore, if what I eat causes my brother or sister to fall into sin, I will never eat meat again, so that I will not cause them to fall"* (1 Cor. 8:13). Even our Lord declared all food clean: *"'Are you so dull?' he asked. 'Don't you see that nothing that enters a person from the outside can defile them? For it doesn't go into their heart but into their stomach, and then out of the body.' (In saying this, Jesus declared all foods clean.)"* (Mark 7:18–19). Knowledge of these scriptures should compel us to give thanks and delight more fully in the food we eat, especially seafood.

Aquaculture is proving a viable source of seafood protein for humanity. Along with the production of seafood, however, comes the responsibility to provide safe seafood for consumers. Food safety is a looming challenge for food, agricultural, and aquacultural industries. During pre-harvest, processing, distribution, and after consumer purchase, careful consideration is taken to make food safe for human consumption. The risk of illness as a result of eating seafood is more likely than consumption of non-seafood meat due to the fact that seafood products are either eaten raw or processed in ways that may not completely kill harmful organisms.[33] In aquacultural systems, safety can be ensured by proper screening and monitoring of juvenile fish and mollusks to ensure no contaminants are introduced into the system. After the animals are matured and prepared for market sale, systems to clean shellfish can be employed to aid in the further reduction of physical, microbiological, and/or viral contaminants.

Technology may, on the one hand, increase safety; but on the other hand, have unexpected harmful results. Automation is expanding in many different industries—from manufacturing to customer service. The aquacultural industry has also employed automation via the use of automated feeders, sampling devices/vehicles, and monitoring systems.[34] An autonomous system can describe any system that gathers information, generates a solution, and then executes an action implementing the solution.[35] While autonomous systems are an exciting area of technology and one that will almost certainly become more necessary in large-scale aquaculture, these systems can have unintended consequences—both technical and human—involving interaction, intentions, and capabilities.

Combinations or teams of vehicles may work in collaboration to collect multi-perspective data and/or to provide vehicle task assistance.[36] These systems are now being developed and implemented within various fields, from the military to environmental monitoring, and can be configured in various ways based on vehicle type, quantity, and collaborative structure.[37] Collaboration is dependent on the type and amount of interaction on the human-robot interface and the methods of vehicle communication.[38] The shared goal of these systems is to make tasks less expensive, safer, and more efficient in order to expand data collection possibilities, minimize risk, and optimize productivity.[39]

Serious ethical and theological implications are linked with autonomous systems—humans are still responsible for these "autonomous" systems, which may be parallel to "ruling over" other creatures (Gen. 1:26). Damage from autonomous agents might be considered in the same light as responsibility for domestic animals in Exodus 21:28–30. The owner of such a system bears responsibility. Theology should be considered regarding the dynamic relationship between humans and their autonomous systems. This goes beyond aquaculture, but the same principle applies: to enhance fruitfulness of creation, to maintain safety, and, ideally, to enhance human life.

A More Sustainable Path

Sustainability has become a significant part of the conversation concerning how to manage our planet and humanity's stewardship of it, especially over the last few decades. Sustainable development, sustainable agriculture, and sustainable aquaculture have been the focus of many publications, with considerations of social, environmental, and economic aspects, sometimes popularly referred to as "people, planet, and profits."[40] Aquaculture is growing; if managed well, it may help reduce pressure on wild fish stocks while providing high quality protein for billions. A theology of sustainable aquaculture will be biblically based and will consider environmental and social conditions while presenting a vision of fruitfulness and responsible stewardship of creation.

One hope is to grow aquaculture enough to allow for a reduction in the stress on worldwide ocean fisheries and restoration of depleted wild fish populations. This would allow for human and aquatic flourishing. Figure 2 suggests possible scenarios based on current wild harvest and aquaculture production levels and growth rates of aquaculture that may allow wild fisheries to begin a restoration process with reduced catch. Based on this, production of aquaculture will likely exceed 200 million metric tons (MMT) by 2050 (using a conservative linear trend based on growth since 2010); wild fishery harvest can be reduced from recent harvests over 90 MMT to a more sustainable 80 MMT, still providing food for a growing world population (estimated growth approximately 2–3 billion additional people during this period).[41]

Total harvest (wild plus aquaculture) is expected to be nearly 300 MMT in 2050, roughly correlating with an increase in world population, but still minimizing negative effects on the oceans. In a more extreme scenario, if aquaculture continues to grow at the historic rate of about 6%, this could lead to over 500 MMT of aquaculture production alone by 2050. Further growth in aquaculture that does not harm oceans, biological stocks, or water quality will be an ongoing task. Continued efforts to reduce wild catch to sustainable levels should be made in concert with increasing well-managed aquaculture production. Theological and values approaches, as well as physical (e.g., engineering, management) and biological techniques used to produce this volume of food, could be what separates a largely sustainable future from one that tragically degrades creation.

One example of an aquaculture success that also helped with restoration is alligator culture. These endangered species were reinvigorated substantially through parallel aquaculture and restoration activities. According to practices overseen by regulators, a certain percentage of alligators are released to the wild at 4 feet (1.2m) in length, when they are likely to survive. As a result of this wisely managed aquaculture and related regulations, wild populations have been substantially increased over four decades and the predation of wild alligators has reduced invasive nutria populations and helped reinvigorate the marsh ecosystem.[42] Simultaneously, a multimillion-dollar business in alligator production has grown up in Louisiana, with a similar-size industry in Florida, indirectly helping pay for restoration efforts.

Various authors address sustainability in three areas: environmental, economic, and social.[43] There seems to be agreement on the belief that sustainability is not simply good but necessary for future society.[44] Such beliefs imply values and ethics. A Christian theology of sustainability must be focused on Christ, his atoning work, and the restoration of humans and all creation that is ongoing. Christian values—including truth and grace—must be at the center of such a theology. Our action originates with Christ's love and flows out to his created order with our desire to care for those he loves. This will result in an emphasis on caring for creation wisely and faithfully while providing for people and other creatures with compassion, both now and in future generations. This, as it turns out, sounds similar to "sustainability."

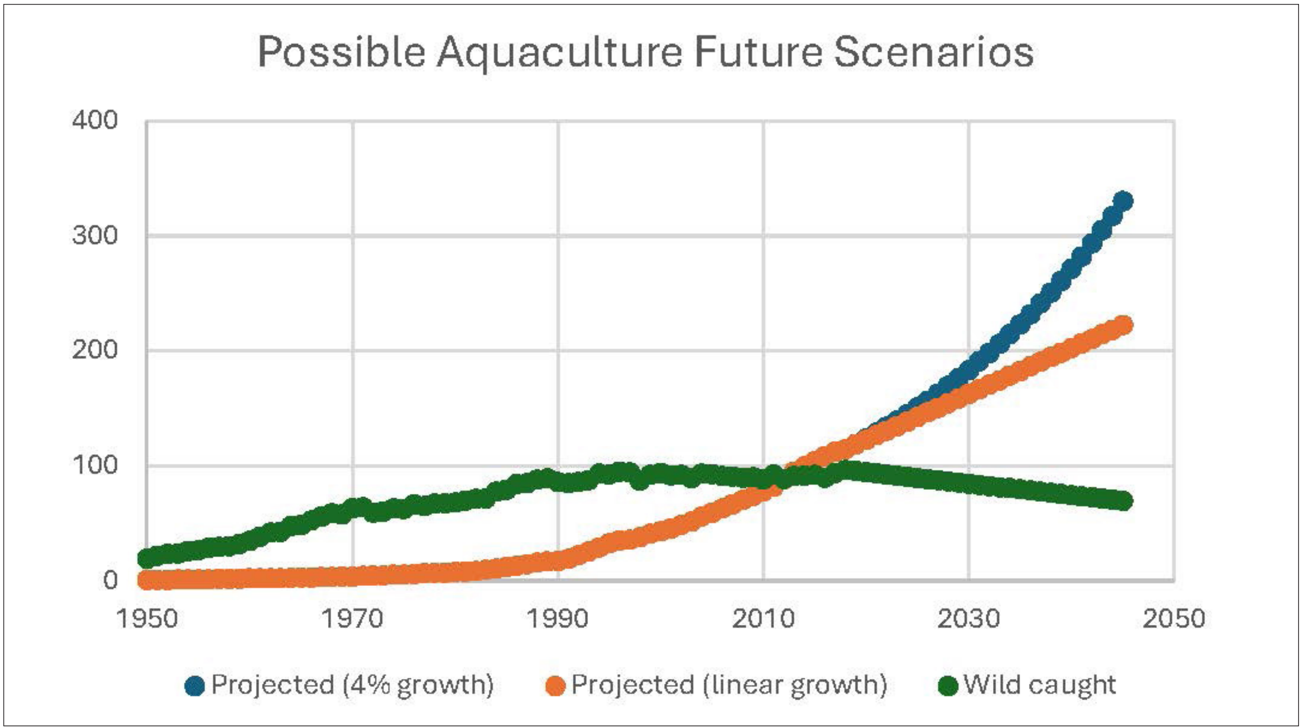


Figure 2. Actual history through the present, and projections based on current levels of wild caught and aquaculture production with conservative linear growth (middle line) based on linear trends from the last decade; and long-term growth rate (upper line) of 6% per year, consistent with aquaculture growth since 1950). Data based on FAO 2020 Fishstat at http://www.fao.org/fishery/statistics. Given past aquaculture growth and expected future trends, wild fisheries could at least partially recover while aquaculture could provide more total protein (aquaculture plus wild fisheries) per person for expected increasing population. The middle (linear growth) model provides more fish protein per person than current totals from aquaculture and wild fisheries, while the higher (6% growth) curve roughly doubles that number by 2045. Units are millions of metric tons (MMT) of annual production.

Long-term sustainability requires each aspect—environmental sustainability (creation care/restoration), sufficient economic return (appropriate use of talents, fair wages), and social and community features (loving our neighbor, thankfulness to God, caring for those in need)—to support a population that can cultivate (Gen. 2:15) and manage resources in a beneficial way. Certain characteristics of sustainability on land are still controversial, but sustainable aquaculture is even earlier in development.[45] Sustainability in aquaculture may mean farming on lower trophic levels by using more plants or algae as feed and less fish meal, or by growing valuable seaweed that cleans the water by absorbing nutrients that could otherwise cause detrimental environmental effects;[46] aquaponics contributes to these desirable outcomes by growing edible plants and fish in parallel systems that increase productivity and minimize environmental pollution.[47] While some cultured species are carnivorous (e.g., salmon, trout), and current models still include their production due to economic demand, these species require more protein—often wild fish—in feed than species lower on the trophic order. Fish such as tilapia and carp can be fed largely plant-based diets, reducing inputs of protein, while filter feeders such as oysters and clams remove algae and other particles from the water column, thus enhancing water quality. In fact, aquaculture's largest production by mass is already aquatic plants: macroalgae or seaweed.[48]

Humans are called to "rule over the fish of the sea" (Gen. 1:26), but the implication is stewardship and caring for these creations—allowing for the fruitfulness of aquatic creatures, not the destruction of aquatic ecosystems. Considering aquaculture as substantially focused on caring for creation and the poor would lead us to harvest this food and also find ways to maintain the fruitfulness of oceanic and aquatic resources. What kind of aquaculture minimizes damage to ocean resources or even helps stressed fisheries recover? How can we avoid overexploitation or damage to the oceans and fisheries, and how can we enhance overall sustainability in aquaculture? A theology which addresses these matters from a biblical standpoint can help undergird a more truly sustainable aquaculture.

Parallels: Sustainability in Agriculture and Aquaculture

Steven Hall proposed a theology of sustainable agriculture in which he suggested that agriculture might include both culture on land (terraculture) and in the water (aquaculture).[49] His main focus was on parallels between the Bible, written across many centuries in nomadic and settled agrarian societies, and our current age, in which we have indeed been fruitful but are now reducing the abundance of other species. There are both secular organizations (e.g., FAO; UN Sustainable Development Organization; Sierra Club) and Christian organizations (e.g., A Rocha, ECHO, Au Sable Institute) which address some of these concerns,[50] but primarily those concerning land-based food and natural systems. As we consider aquaculture, the fastest growing protein sector (fig. 3),[51] and the growth of food, fiber, and other products in the water, some new theological observations as well as technological innovations are worth considering. Underlying each of these technologies are implications for economic, environmental, or social stability. At a theological level, considerations of stewardship of the environment, compassion toward workers and other creatures, and stewardship to provide for ongoing abundance both for humans and for other creatures, are central themes.

What unique contributions can scientists and theologians offer that enhance our current approach to sustainability? In particular, definitions of sustainable development (e.g., of societies) include, at least partially, an ethical aspect—often normative.[52] One ethical requirement is that such development must not impose an undue burden on future generations. In agriculture and aquaculture,[53] the ability to maintain productivity, by both the producer and the region, is a parallel requirement. Sustainability also implies harvesting at a rate that allows the ecosystem to regenerate in a reasonable time period.[54]

As noted, Hall aimed at addressing practical and theological questions concerning sustainability of agriculture. He addressed ethics, the concept of stewardship, economics, communities, and intergenerational equity and justice for the poor, and he concluded with suggestions on redeeming and restoring God's creation and the practice of agriculture. He also cited a handful of references to aquaculture[55] and the statement: "Aquaculturists need to consider how their production impacts the water, native fish stocks, and other aspects of their environment,"[56] acknowledging Dayton Roberts and Paul Pretiz's *Down to Earth Christianity*, and Wes Jackson, Wendell Berry, and Bruce Colman's *Meeting the Expectations of the Land*, which have theological and values aspects.[57]

Hall included insights from both the "book of scripture" and the "book of nature" point of view and acknowledgment of long-standing theological traditions that address sustainability. Some of these, such as the concept of Sabbath for the land found in the book of Leviticus, are still relevant today, albeit in a somewhat changed physical and cultural environment. Other perceptions are generally accepted tenets of theology with applications to sustainability, especially with the production of food. Finally, there are prophetic passages, both challenging (e.g., *"those who destroy the earth shall be destroyed,"* Rev. 11:18) and optimistic (*"I saw a renewed Heaven and a renewed Earth …,"* Rev. 22:1) about the future. Christians are called to follow the Lord, to care for the least of these, and by extension, to care for both people and creation. In the case of aquaculture, this means focusing on specific ways we can steward and manage aquatic resources to provide food for growing populations while also providing for a prosperous creation and future generations. Some specific areas are critical to consider and should address theology and sustainability in aquaculture.

One hope of this article is to suggest a path forward. This path should be universal in that the broad notions should be acceptable to all reasonable people. It should also be of specific interest to Christians, and hopefully, it will encourage them to address enhanced methods to feed the world's people, especially the poor (*"whoever feeds the least of these feeds me,"* Matt. 25:40). It should describe ways to be fruitful while also allowing God's good creation to do the same. A truly biblical vision should focus on restoring or enhancing the abundance and productivity of the waters, not only from the point of beneficial human use but also from the point of natural biodiversity, ecosystem health, and general stewardship of natural aquatic systems.

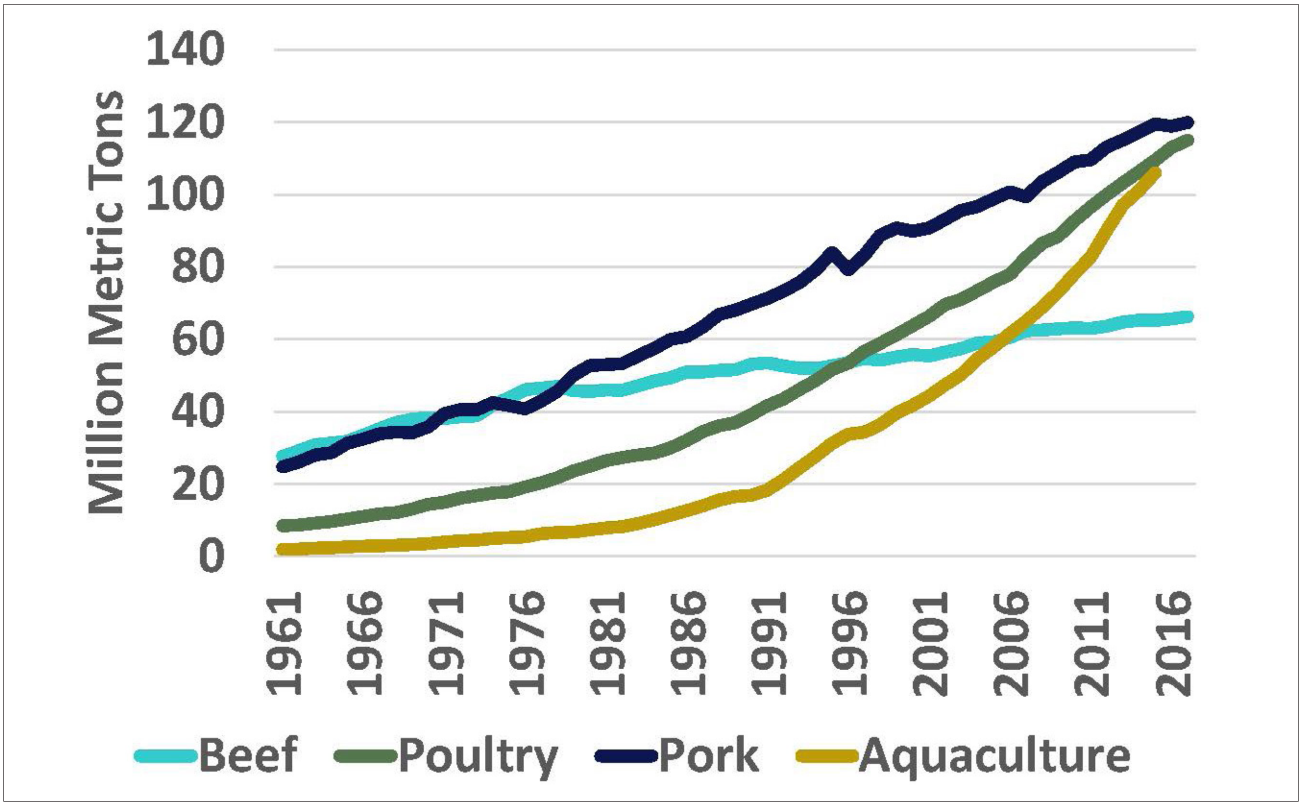


Figure 3. Aquaculture has now passed beef as a source of protein worldwide and is approaching the production of poultry and pork (FAO). Fish are known to be fundamentally good converters of protein, in some cases producing nearly a pound of fish per pound of feed. The support of the water allows less energy to go to building a skeleton and more to biomass. Fish are also poikilotherms, so they do not expend energy maintaining body temperature in most cases. However, despite these efficiencies, concerns about water quality, food quality, natural fisheries, and outcomes on traditional fishing communities are each important to consider (data from UN FAO 2018).

Aquaponics (see fig. 4) is a historic technology that has been modernized and effectively used, not just to survive, but to thrive.[58] This technology has been the subject of much research in the past few decades and offers immense potential in terms of productivity, conservation, waste valorization, and resource use efficiency that can be influential in overall sustainability. It combines the production of fish and plants in one system in which the plants, fish, and nitrifying bacteria develop a symbiotic relationship that creates a micro-ecosystem which makes it sustainable. The modularity of aquaponics allows its application or operation even in urban areas; such a system could bring it closer to the consuming population and eventually reduce carbon footprint.[59]

Another biological concern focuses on the desire to raise carnivorous species from salmon to tuna, impling that we are feeding one species of fish to raise another, clearly not encouraging the recovery of stressed fisheries. Efforts toward feeding more plant-based food to these fish, that is, raising herbivorous fish or even filter-feeding bivalves such as oysters and clams, could address this area. One little-known fact is that the top aquaculture product worldwide is seaweed or aquatic plants.[60] The aquatic plant sector could expand, increasing the output of aquaculture while minimizing environmental damage, or, if carefully managed, it could be used to help clean water and restore ocean health.[61] One practical and ethical challenge is that the value of seaweed is often lower than that of carnivorous fish, pushing producers to focus more on less-sustainable salmon and less on macroalgae, for example. Finding ways to enhance the value or to provide payments for the ecological value of removing nutrients might help encourage farmers to focus more on sustainable plant products.

Some of these techniques to reduce stress on the ocean focus on growing aquatic species low on the food chain, such as plants, algae, and filter feeders—for example, shellfish that filter algae and other material in the water, all of which can enhance water quality, provide habitat, and still produce aquatic food. Improving our understanding of reef systems, microalgae, and macroalgae (seaweed) could help enhance productivity of the oceans while maintaining or perhaps restoring some species and ecosystems.[62]

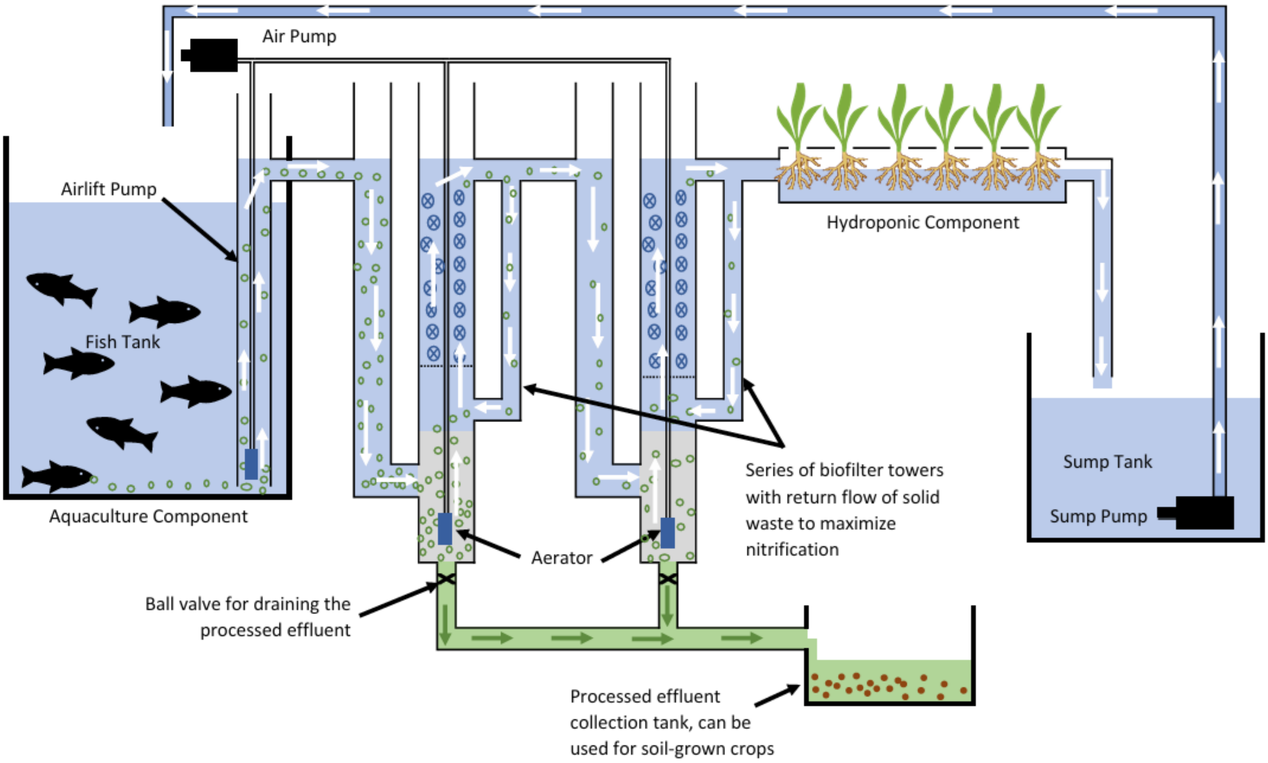


Figure 4. Flow diagram of a recirculating aquaponics system with series of biofilter towers to optimize the nitrification of ammonia into nitrite and nitrate. The nitrified nutrient is readily used by plants and cleans up the water before returning to the fish tank. This design uses an airlift pump and submersible pump to recirculate the water. The airlift pump also helps to maintain the dissolved oxygen and disperse carbon dioxide. An aerator is provided at the bottom of the biofilter tower and acts as "mechanical digester" to extract nutrients from the effluent. The collected solids will then be drained out and can be used as fertilizer and soil enhancer for soil-grown crops.

There is potential to responsibly use enhanced design techniques for shellfish culture systems to improve water quality and to grow food. However, responsible management of technology has theological and ethical dimensions which extend beyond the purely biological. Specifically, automation and autonomous systems are technological sectors that are growing fast, with substantial automation already used and more use of autonomous systems expected; the theological and praxis aspects of these technologies should be considered carefully.

Technology in Service to Sustainability

The goal of any kind of innovation is to reduce current problems and avoid future ones. This is especially true for sustainable aquaculture. Unpiloted surface vehicles (USVs) are being used to collect water quality data to evaluate existing or potential aquaculture operation sites.[63] Autonomous underwater vehicles (AUVs) are traveling beneath the surface to inspect and manage net pens.[64] Even unpiloted aerial vehicles (UAVs) have been made capable to estimate chlorophyll *a* concentrations to help monitor the health of a body of water.[65] Open-ocean aquaculture is expensive in terms of labor and maintenance costs, and therefore many researchers and aquaculture businesses are moving in the direction of autonomy.[66] This progression toward autonomy can have profound effects on the industry.

Autonomy in aquaculture has the ability to greatly reduce cost, man-hours, and risks to safety. Ingrid Bouwer Utne et al. claim that there is limited focus in research on health and safety in aquaculture.[67] There were over 1,400 injuries from 1988 to 2013, and approximately 33 fatalities from 1982 to 2013, in Norway alone.[68] The Code of Ethics for Engineers, written by the National Society of Professional Engineers, states that "engineers shall hold paramount the safety, health, and welfare of the public."[69] Sharkey makes the contention that "public and international discussion is vital in order to set policy guidelines for ethical and safe application before the guidelines set themselves."[70]

Many questions relate to purpose—of devices and of human beings. Human qualities include the fruits of the spirit (Gal. 5:22), which culminate in love. How can we create and guide automated and autonomous systems that encourage people in these fruitful and loving directions? Proponents of sustainable aquaculture by automation must consider how to address these problems on the future inclusion of autonomous vehicles and systems.

Food Safety and Added Value

Keeping food safe to eat is critical to human health. Depuration is a processing method in which filter-feeding organisms harboring contaminants are allowed to filter feed in a clean water source, thus allowing for the natural purging of contaminants from the organism.[71] These systems can even be enhanced by manipulating key depuration parameters such as processing time, water temperature, water flow rate, and water salinity. For example, A. M. Larsen et al. found that high salinity was an effective component in reducing *Vibrio parahaemolyticus* and *Vibrio vulnificus* in live oysters during depuration.[72] Cooking seafood is always a suggested method of reducing food pathogens, but cooking often alters food product quality. Application of processing methods that do not change the notable characteristics of seafoods, but effectively eliminate human pathogens, is a problem that research is actively addressing.

Aquatic animals intended for food, including bottom dwellers and filter feeders in particular, are strongly affected by their environment. The long-term approach to food safety involves acknowledging and responsibly stewarding water resources. Among other steps implied by this approach is the willingness to manage water quality, which implies societal responsibilities upstream. Specifically, proper treatment of human and livestock wastewater is essential, and industries and individuals must act responsibly to reduce toxic effluents in surface waters. These waters hold consequences for us all, with downstream communities, both human and aquatic, experiencing more-pronounced effects.

Parallel to the concept of food safety is the idea of adding value to seafoods by various forms of healthy handling and processing. As consumers of seafood, it is imperative that we take on a greater responsibility in the stewardship of aquatic life. Currently, we see that aquaculture can provide an excellent alternative source of protein for humans. The majority of fish feed is turned into energy for the growing fish, so waste is minimal if systems are planned well.

Aquaculture also has the potential to relieve stresses on lands that have been over-tilled and depleted of nutrients. Seafood waste can contribute to fertility or serve other useful purposes. For example, recycled oyster shells may be one method of sustainable carbon sequestration, while algae can be used for renewable biodiesel production.[73] Similarly, hydroxyapatite, beneficial for medical bone reconstruction, has been produced from components of fish bones.[74] Current and future research continues to make use of aquatic systems and seafood and their subsequent waste.

Theological and ethical considerations regarding value-added seafood encompass both safety and quality, emphasizing high protein content, low fat, and desirable nutrition. Fundamentally, aquaculture should be a way to maintain good quality, as the feeds are often provided and controlled more than for wild fish. However, mislabeling can be unethical,[75] and the health benefits of aquatic products can be reduced by processing that diminishes nutrition content or adds unhealthy calories (e.g., breading or frying). By recognizing the value of various aquatic organisms and the value of their various components, not only can we more fully utilize but also appreciate and enjoy the bounty the Lord provides.

We should understand, in modern times, that God wants us to enjoy his creation and celebrate his goodness by consuming aquatic animals and plants. For example, Jesus, before his ascension in Luke 24, ate a piece of broiled fish. He and the disciples often fished for food since seafood was a vital food source in ancient Jewish culture. Ultimately, we should be reminded that human consumption of seafood, along with responsible stewardship of the planet's waters, aquatic life, and seafood byproducts, not only contributes to the growth of the seafood and aquaculture industry, but it also allows us, as stewards, to participate in a plan for humanity that traces back to the beginning (see Gen. 2:15, where *A'dam* is instructed to "protect and serve" creation).

Conclusions and Best Practices

Aquaculture is the fastest-growing protein sector. With a growing world population expected to add more than 2 billion people worldwide by 2050, it is critical and ethical that we produce healthy, efficient food such as fish and aquatic plants. However, various technological, ecological, and social complications remain; a theology of sustainable aquaculture must address these as they emerge and are introduced. Biblically, we are stewards with responsibility to care for God's creation. We can enjoy seafood, whether wild caught or cultured, but should do so wisely, and in such a way that water quality and fisheries, as well as the communities tied to these resources, remain healthy or are restored to productivity and are preserved for future generations.

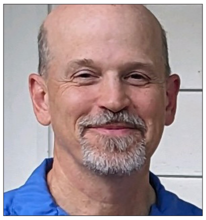
Some practical conclusions are appropriate. Scientists, regulators, businesses, coastal communities, and consumers—all can learn and act wisely.[76] Regulators can consider long-term implications of development choices, infrastructure placement, and restoration/conservation of aquatic resources. Businesses are encouraged to prioritize the production of valuable products (aquatic foods, fuels, and fibers are indeed valuable) in a sustainable way, as we have suggested. Coastal communities can consider further development in light of scientific findings and wisely invest (or defer investment) in ways that can sustain and protect both human communities and the ecosystems they depend on. Consumers can be aware that aquatic products are generally healthy and efficient sources of protein, whether cultured or wild caught. They can choose more aquatic plants (e.g., seaweed and related products), filter feeders (e.g., mussels, oysters, clams), and finfish and shellfish that are herbivorous or omnivorous (e.g., tilapia, pangasius, herring, anchovies), and limit the amount of large carnivorous fish (e.g., tuna, salmon) that require more net resources and may also bioaccumulate undesired toxins (these are often marked with a warning to limit consumption).

All of this is presented humbly, as consistent with current knowledge and subject to further investigation and interpretation, but we hope this encourages conversation about how to make aquaculture more sustainable by applying both scientific and theological insights. Theologically, we are still looking forward to a fully renewed earth that explicitly includes aquatic systems as referenced in Revelation:

> *Then the angel showed me the river of the water of life, as clear as crystal, flowing from the throne of God and of the Lamb down the middle of the great street of the city. On each side of the river stood the tree of life, bearing twelve crops of fruit, yielding its fruit every month. And the leaves of the tree are for the healing of the nations.* (Rev. 22:1–2)

As children of God, we are called to steward his creation, including water ecosystems, humans, and other creatures. In short, aquaculture is expanding, and will continue to grow worldwide. We are called to manage the growth of aquaculture in a way that glorifies God and continues to provide a fruitful (and restored) planet with healthy aquatic ecosystems and creatures.

About the Authors



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Steven Hall is professor and director of the Marine Aquaculture Research Center at North Carolina State University, Raleigh, NC. His focus is on aquacultural and coastal bioengineering, with teaching, research, and extension service responsibilities. He coedits the journal Aquacultural Engineering. *He is former president of the Aquacultural Engineering Society and a Fellow of the American Scientific Affiliation.*

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Matthew Campbell worked as an engineering consultant, serving clients on coasts around the world. He then earned a PhD in biological and agricultural engineering at North Carolina State University (NCSU) focusing on aquaculture engineering in the marine environment. He currently is adjunct faculty at NCSU and president at Natrx, a company focused on coastal resiliency, reef restoration, living shorelines, and nature-based solutions.

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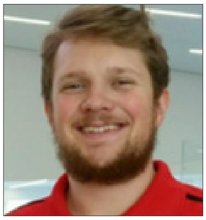

Russell Smith

Edwin "Russell" Smith V (MS from North Carolina State University) has worked on the design and testing of cooperative, heterogeneous uncrewed aerial and surface vehicle system to provide near real-time water quality data in nearshore aquaculture production environments. Russell now works with Atlantic Sapphire to produce sustainable aquaculture products.

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Christopher Pascual is a PhD student in biological and agricultural engineering at North Carolina State University. He holds a master's degree in agricultural engineering at Central Luzon State University, Philippines, where he also serves as lecturer, researcher, and extension worker, specializing in controlled environment, vertical, and urban farming. His research focuses on aquaponics, particularly marine applications.

Laura Newsom

Laura Newsom is an undergraduate researcher under the mentorship of Steven Hall and Christopher Pascual. She is currently pursuing a bachelor's degree at North Carolina State University in chemical engineering with a concentration in sustainable engineering, energy, and the environment.

Notes

[1]Food and Agriculture Organization of the United States (FOA), "The State of World Fisheries and Aquaculture 2020," https://www.fao.org/state-of-fisheries-aquaculture/2020/en/, https://www.fao.org/3/ca9229en/ca9229en.pdf, hereafter FAO 2020.

[2]Ibid. This report includes graphs and figures attesting to the dramatic increase in aquaculture over the last 50 years. Fish consumption is now greater than beef consumption worldwide.

[3]World Bank, "Fish to 2030: Prospects for Fisheries and Aquaculture. Agriculture and Environmental Services," Discussion Paper 03 (Washington, DC: World Bank Group, 2013), Report number 83177-GLB, http://documents.worldbank.org/curated/en/458631468152376668/Fish-to-2030-prospects-for-fisheries-and-aquaculture. This document analyzes global fisheries (wild fish) and aquaculture, noting that fish are perhaps the most efficient form of protein production to feed growing world populations. As a note, some fish are relatively inefficient or expensive (note sturgeon caught or farmed for caviar, sold for many dollars per ounce), while others are quite hardy, efficient, and typically "low trophic level"—e.g., primarily plant eaters, omnivores, or filter feeders. These are the fish (think catfish, tilapia, or perhaps oysters) that may actually "feed the poor."

[4]FAO 2020.

[5]A number of authors have explored the history of aquaculture in various cultures. Aquaculture was generally at a very local level: e.g., ponds in Europe or Hawaii; coupling of fish with plants and other livestock in historic China. See, e.g., Fangzhou Hu et al., "Development of Fisheries in China," *Reproduction and Breeding* 1, no. 1 (2021): 64–79, https://doi.org/10.1016/j.repbre.2021.03.003. Modern aquaculture has expanded in both scale and complexity, using advanced genetics, filtration, feeding, and management.

[6]Rosamond Naylor et al. reviewed data at that time which revealed a number of problems, specifically, that bycatch from (wild) marine fisheries was often used to make fish feeds, and since these fish stocks were often over exploited, they suggested biological limits. This work set the aquaculture industry to move toward algae, plant, and other "lower trophic level" feeds and to limit wild fish meal in aquaculture. Rosamond L. Naylor et al., "Effect of Aquaculture on World Fish Supplies," *Nature* 405 (2000): 1017–24, https://doi.org/10.1038/35016500.

[7]Martha Iwamoto et al., "Epidemiology of Seafood-Associated Infections in the US," *Clinical Microbiology Review* 23, no. 2 (2010): 399–411, https://doi.org/10.1128%2FCMR.00059-09.

[8]FAO 2020.

[9]FAO 2020; The National Oceanic and Atmospheric Administration (NOAA) yearly publications also provide additional (primarily US) information. Especially see, "Fisheries of the United States, 2005," *NOAA Fisheries*, January 24, 2006, last updated January 24, 2018, https://www.fisheries.noaa.gov/feature-story/fisheries-united-states-2005; and "Fisheries of the United States, 2018," *NOAA Fisheries*, February 21, 2020, https://www.fisheries.noaa.gov/feature-story/fisheries-united-states-2018.

[10]Colin G. Scanes, "Animal Agriculture: Livestock, Poultry, and Fish Aquaculture," in *Animals and Human Society*, ed. Colin G. Scanes and Samia R. Toukhsati (Cambridge, MA: Academic Press, 2018), 133–79, https://doi.org/10.1016/B978-0-12-805247-1.00007-1.

[11]Jonathan Shepherd, "The Lessons from Intensive Livestock Development for Aquaculture," in *Global Trade Conference on Aquaculture: 29–31 May 2007—Qingdao, China*, ed. Richard Arthur and Jochen Nierentz (Rome, Italy: FOA, 2007), 249–57. This article recognizes some of the unforunate results that have occurred with land-based animals, including pollution, disease, and animal treatment.

[12]FOA 2020 acknowledges both the growing population and reduced fisheries (85% of fish stocks worldwide are fully fished or overfished).

[13]Naylor et al., "Effect of Aquaculture on World Fish Supplies."

[14]Stefano B. Longo et al., "Aquaculture and the Displacement of Fisheries Captures," *Conservation Biology* 33, no. 4 (2019): 832–41, https://doi.org/10.1111/cobi.13295, argue that aquaculture should help reduce stress on wild fisheries, but despite efforts to reduce the use of fish meal, the total volume of aquaculture has not yet enhanced wild fisheries. George S. Lockwood, in his book *Aquaculture: Will It Rise to Its Potential to Feed the World?* (San Francisco, CA: Blurb, 2017), asserts that "Aquaculture is the most environmentally sustainable means to feed the population boom that threatens the planet" (book back cover). He addresses a series of concerns including regulations, public image, and various business and practical implications. The jury is still out on whether aquaculture will have a net negative or positive effect on wild fisheries. Rosamond L. Naylor et al., "A 20-Year Retrospective Review of Global Aquaculture," *Nature* 591 (2021): 551–63, https://doi.org/10.1038/s41586-021-03308-6, addressed some further changes, noting some improvements and some additional setbacks.

[15]In some ways, the physics and biology are limiting factors, but addressing these is a values or ethics question, and will require both individual (farmers, fishers) and group (governments, policy, NGO, business) actions.

[16]Both Naylor and Longo, in their writings, asked but did not fully answer questions about what effects aquaculture may have long term. Longo ran seven models trying to predict these and did not get convincing answers either way.

[17]Amos O. Arowoshegbe, Emmanuel Uniamikogbo, and Olufemi O. Gina, "Sustainability and Triple Bottom Line: An Overview of Two Interrelated Concepts," https://www.researchgate.net/publication/322367106_SUSTAINABILITY_AND_TRIPLE_BOTTOM_LINE_AN_OVERVIEW_OF_TWO_INTERRELATED_CONCEPTS look at the "triple bottom line" of social, environmental, and economic sustainability. Other authors apply these concepts directly to aquaculture. See, for example, Mahfuzur Shah et al., "Microalgae in Aquafeeds for a Sustainable Aquaculture Industry," *Journal of Applied Phycology*, 30, no. 1 (2018): 197–213, https://link.springer.com/article/10.1007/s10811-017-1234-z.

[18]Rubén Vita and Arnaldo Marín, "Environmental Impact of Capture-Based Bluefin Tuna Aquaculture on Benthic Communities in the Western Mediterranean," *Aquaculture Research* 38, no. 4 (2007): 331–39, https://doi.org/10.1111/j.1365-2109.2007.01649.x, described the "classic" capture of tuna to fatten them in cages and noted not only that this affects wild tuna, but also that the wastes from the sea cages stressed other animals in a radius of at least 200 meters around the structure.

[19]Johann Bell et al., "Pathways to Sustaining Tuna-Dependent Pacific Island Economies during Climate Change," *Nature Sustainability* 4 (2021): 900–910, https://doi.org/10.1038/s41893-021-00745-z, noted that a number of these economies are dependent on wild capture and sale of tuna species, and suggested ways to enhance sustainability via various management techniques.

[20]Gorana Jelić Mrčelić et al., "An Overview of Atlantic Bluefin Tuna Farming Sustainability in the Mediterranean with Special Regards to the Republic of Croatia," *Sustainability* 15, no. 4 (2023): 2976, https://doi.org/10.3390/su15042976, acknowledged the challenges of tuna capture and fattening, and addressed the need for "future sustainable closed-cycle tuna farming …"

[21]Brendan F. Wringe et al., "Extensive Hybridization Following a Large Escape of Domesticated Atlantic Salmon in the Northwest Atlantic," *Communications Biology* 1 (2018): 108, https://doi.org/10.1038/s42003-018-0112-9, noted that hybrids between cultured and wild salmon accounted for 27% of salmon sampled; they were found in 17 out of 18 rivers sampled, suggesting a large genetic change in the area. It is not clear what the long-term repercussions may be.

[22]For example, Naylor et al., "Effect of Aquaculture on World Fish Supplies"; Naylor et al., "A 20-Year Retrospective Review of Global Aquaculture"; and Mrčelić et al., "An Overview of Atlantic Bluefin Tuna Farming Sustainability."

[23]Michael B. Timmons and Brian J. Vinci, *Recirculating Aquaculture, 5th ed.* (Ithaca, NY: Ithaca Publishing, 2022).

[24]Atlantic Sapphire website, quotations from Sustainability, Our Mission: Better for All of Us; and Sustainability, Innovation: Ocean Safe, accessed April 6, 2024, https://atlanticsapphire.com/sustainability/.

[25]Naylor et al., "Effect of Aquaculture on World Fish Supplies."

[26]Naylor et al., "A 20-Year Retrospective Review of Global Aquaculture"; Lucia S. Herbeck et al., "Decadal Trends in Mangrove and Pond Aquaculture Cover on Hainan (China) since 1966: Mangrove Loss, Fragmentation and Associated Biogeochemical Changes," *Estuarine Coastal and Shelf Science* 233 (2020): 106531, https://doi.org/10.1016/j.ecss.2019.106531; and H. Q. Nguyen et al., "Socio-Ecological Resilience of Mangrove-Shrimp Models under Various Threats Exacerbated from Salinity Intrusion in Coastal Area of the Vietnamese Mekong Delta," *International Journal of Sustainable Development and World Ecology* 27, no. 7 (2020): 638–51, https://doi.org/10.1080/13504509.2020.1731859.

[27]Rex Hall Caffey, "Quantifying Sustainability in Aquaculture Production," PhD diss., Lousiana State University, 1998, https://repository.lsu.edu/gradschool_disstheses/6809, focused on sustainability in aquaculture; and Rex H. Caffey, Robert P. Romaire, and J. W. Avault Jr., "The Sustainability of Crawfish Aquaculture," *World Aquaculture* 27, no. 2 (1996): 18–23. Both papers recognize that sustainability is critical for aquaculture to flourish. While not explicitly theological, value statements consistent with a Christian worldview are explored in these works.

[28]Longo et al., "Aquaculture and the Displacement of Fisheries Captures," is one example of a work questioning the sustainability of current aquaculture practices.

[29]Personal communication, Benjamin Reading, North Carolina State University Department of Applied Ecology, 2020, claims that the domesticated striped bass at the base of the now $100 million plus hybrid striped bass industry is only on its eighth generation, while Terry Tiersch, Lousiana State University Renewable Natural Resources, has worked with catfish to "modernize" the industry but acknowledges the whole catfish industry is genetically "very young."

[30]One positive view of AquAdvantage Salmon (owned by AquaBounty Technologies) is Henry Clifford, "AquAdvantage Salmon—A Pioneering Application of Biotechnology in Aquaculture," *BMC Proceedings* 8, suppl. 4 (2014): O31, https://doi.org/10.1186%2F1753-6561-8-S4-O31. He notes that these (Atlantic with some inserted transgene from Chinook salmon) salmon reach market size in half the time and will be available only as "all female, sterile fish." They will further be required to be maintained in a freshwater, land-based, biosecure system. An alternative viewpoint is represented by Rebecca Voelker, "New on the Menu: Genetically Modified Salmon," *Journal of the American Medical Association* 315, no. 1 (2016): 20, https://doi.org/10.1001/jama.2015.17339. She notes that the FDA has approved this animal, but that it "meets the definition of a drug" (due to added growth hormones and activators). The fact that this fish also includes genetics from the pout fish is also more apparent in this article than in the article by Clifford.

[31]This threat includes two problems: that of invasive species, and that of genetic changes, as explained further in Carol A. Stepien, Matthew R. Snyder, and Anna E. Elz, "Invasion Genetics of the Silver Carp *Hypophthalmichthys molitrix* across North America: Differentiation of Fronts, Introgression and eDNA Metabarcode Detection," *PLoS One* 14, no. 3 (2019): e0203012, https://doi.org/10.1371/journal.pone.0203012.

[32]Naylor et al., "A 20-Year Retrospective Review of Global Aquaculture."

[33]Iwamoto et al., "Epidemiology of Seafood-Associated Infections in the United States."

[34]Jens G. Balchen, "Automation in Fisheries and Aquaculture Technology," in *Control Systems, Robotics and Automation* 19, in *Encyclopedia of Life Support Systems (EOLSS),* developed under the auspices of the UNESCO (Paris, France: Eolss Publishers, 2002), https://www.eolss.net/sample-chapters/c18/E6-43-35-05.pdf.

[35]Mike Salem addresses basic definitions of autonomy in "What Is an Autonomous System?," *Udacity,* September 24, 2018, 3-min. read, https://www.udacity.com/blog/2018/09/what-is-an-autonomous-system.html, while Noel Sharkey discussed some of the ethical questions in these areas in "The Ethical Frontiers of Robotics," *Science* 322, no. 5909 (2008): 1800–1801, https://www.science.org/doi/10.1126/science.1164582.

[36]Yong Ma et al. explored how multiple vehicles can communicate effectively in "Cooperative Communication Framework Design for the Unmanned Aerial Vehicles-Unmanned Surface Vehicles Formation," *Advances in Mechanical Engineering* 10, no. 5 (2018): https://doi.org/10.1177/1687814018773668, while Man Zhu and Yuan-Qiao Wen addressed engineering design of collections of vehicles in an aquatic environment in "Design and Analysis of Collaborative Unmanned Surface-Aerial Vehicle Cruise Systems," *Journal of Advanced Transportation* 2019 (January 14, 2019), https://doi.org/10.1155/2019/1323105.

[37]Zhu and Wen, "Design and Analysis of Collaborative Unmanned Surface-Aerial Vehicle Cruise Systems"; and Eduardo Pinto, Pedro Santana, José Barata, "On Collaborative Aerial and Surface Robots for Environmental Monitoring of Water Bodies," in *Technological Innovation for the Internet of Things*, DoCEIS 2013. IFIP *Advances in Information and Communication Technology*, vol. 394, ed. Luis M. Camarinha-Matos, Slavisa Tomic, and Paula Graça

(Berlin, Heidelberg: Springer, 2013), 183–91, https://doi.org/10.1007/978-3-642-37291-9_20; and Joshua N. Weaver, A. A. Arroyo, and E. M. Schwartz, "Collaborative Coordination and Control for an Implemented Heterogeneous Swarm of UAVs and UGVs" (unpublished PhD diss., 2014). Each address the computer codes required for such collaborative coordination and control of multiple vehicles. However, they only hint at the ethical or theological implications of multiple different types of highly autonomous robots in the environment.

[38]Arthur Zolich et al., "Survey on Communication and Networks for Autonomous Marine Systems," *Journal of Intelligent & Robotic Systems* 95, no. 3-4 (2019): 789–813, https://doi.org/10.1007/s10846-018-0833-5, provide a recent update, noting that the field of autonomous marine systems is expanding substantially for both resource extraction and security reasons. Steven G. Hall, Daniel D. Smith, and Troy Davis, "Design of a Communications System between Multiple Autonomous Vehicles," paper presented at the American Society of Agricultural and Biological Engineers Annual International Meeting, Reno, NV, June 21–24, 2009, https://www.researchgate.net/publication/271420802_Design_of_a_communications_system_between_multiple_autonomous_vehicles. This paper does acknowledge the possibility of using groups of autonomous vehicles for aquatic- and aquaculture-related activities.

[39]Sierra Young et al., "Robot-Assisted Measurement for Hydrologic Understanding in Data Sparse Regions," *Water* 9, no. 7 (2017): 494, https://doi.org/10.3390/w9070494 address the use of autonomous vehicles for water-related work, specifically in remote areas.

[40]James L. Anderson et al., "The Fishery Performance Indicators: A Management Tool for Triple Bottom Line Outcomes," *PLoS One* 10, no. 5 (2015): e0122809, https://doi.org/10.1371/journal.pone.0122809; Arowoshegbe, Uniamikogbo, and Gina, "Sustainability and Triple Bottom Line," and others acknowledge the "triple bottom line."

[41]FAO 2020; OECD-FAO Agricultural Outlook 2014–2023: FISHERIES—OECD-FAO Agricultural Outlook 2014–2023 provides data which were used (along with other projections) to create figures 1–3. Data used was from FAO; this and other data is now available at OECF Data Explorer, https://data.oecd.org/.

[42]Mary Nickum et al., "Alligator (*Alligator mississippiensis)* Aquaculture in the United States," *Reviews in Fisheries Science and Aquaculture* 26, no. 1 (2018): 86–98, https://doi.org/10.1080/23308249.2017.1355350, provide a more complete history of the aquaculture industry (now valued at over $70 million in Louisiana alone), and the parallel work to restore and maintain healthy wild alligator populations. There is tension, especially in areas where human development encroaches on habitat. Alligators or other species that are released need healthy environments to live in.

[43]Peter Glavič and Rebeka Lukman, "Review of Sustainability Terms and Their Definitions," *Journal of Cleaner Production* 15, no. 18 (2007): 1875–85, https://doi.org/10.1016/j.jclepro.2006.12.006, created "sustainability axes" to try to map specific concerns and look at optimization or acceptable balances between different aspects of sustainability. This implies some level of tension in sustainable production.

[44]Julia Moore et al., "Developing a Comprehensive Definition of Sustainability," *Implementation Science* 12 (2017): article 110, https://doi.org/10.1186/s13012-017-0637-1, noted that there are many definitions of sustainability that approach from different angles. Herman Daly, in *Beyond Growth: The Economics of Sustainable Development* (Boston, MA: Beacon Press, 1997); and later with coauthor Joshua Farley, in *Ecological Economics: Principles and Applications*, 2nd ed. (Washington, DC: Island Press, 2010), recognized one of these limits to sustainability: the physical limit of the earth's ecosystem to handle waste from our society. While the physical statements made are generally not in doubt (e.g., rising carbon dioxide levels in the air, increasing levels of long-lasting chemicals in the water, and increasing amounts of plastics in the environment), the field of ecological economics continues to clash with the ruling neoclassical economics that focuses on growth, often at the expense of sustainability.

[45]Anderson et al., "The Fishery Performance Indicators"; and Danis Maulana, Merlin Dyah Wati, and Mirza Safitri Agatha Putri, "Optimization of Small Fisheries Enterprise with Fishery Performance Indicators through Triple Bottom Line," *Jurnal Entrepreneur dan Entrepreneurship* 6, no. 2 (2017): 71–78, https://doi.org/10.37715/jee.v6i2.642, argue that the business side is important, and that environmental and social aspects should be brought into the business model of fisheries and aquaculture.

[46]Geddie and Hall focused on developing siting tools for siting macroalgae farming. As the industry develops, other tools will be needed. Alexander W. Geddie and Steven G. Hall, "Development of a Suitability Assessment Model for the Cultivation of Intertidal Macroalgae in the United States," *Science of the Total Environment* 699 (2020): 134327, https://doi.org/10.1016/j.scitotenv.2019.134327.

[47]James E. Rakocy, "Aquaponics: The Integration of Fish and Vegetable Culture in Recirculating Systems," paper presented at the Caribbean Food Crops Society 30th Annual Meeting, St. Thomas, Virgin Islands, July 31–August 5, 1994, https://doi.org/10.22004/ag.econ.258746.

[48]FAO 2016, FAO 2018, and FAO 2020 provide substantial data including much of the data presented in this article. Extensive discussion of fisheries and aquaculture is provided in these reports, whereas we present data to help consider ethical and theological perspectives on this practical and growing field.

[49]Steven Hall, "Toward a Theology of Sustainable Agriculture," *Perspectives on Science and Christian Faith* 54, no. 2 (2002): 103–07, https://www.asa3.org/ASA/PSCF/2002/PSCF6-02Hall.pdf, addressed this unique intersection. Few authors before or since have tackled sustainability of aquaculture from a theological perspective.

[50]A Rocha, https://www.arocha.us/, accessed February 2000, has a broad array of environmental activities and is worldwide, with a tagline "Living God's call to care for creation"; Au Sable Institute, https://www.ausable.org/, provides educational and research experiences for K–12, undergraduate, and the public, with a current tagline "Serve. Protect. Restore," accessed April 2024; and ECHO is Educational Concerns for Hunger and has strongly applied international sustainable agriculture aspects, with a tagline "Hope Against Hunger," https://www.echonet.org, accessed April 2024. Regent Professor Emeritus Loren Wilkenson and team have produced a video series focusing on sustainable agriculture and food,

called Food Forethought, https://www.regentaudio.com/products/food-forethought, with consideration of theological implications of agriculture, food choices, and related topics.

[51]FAO 2020, fig. 3.

[52]See Remigijus Ciegis, Jolita Ramanauskiene, and Bronislovas Martinkus, "The Concept of Sustainable Development and Its Use for Sustainability Scenarios," *Engineering Economics* 62, no. 2 (2009): 28–37; David W. Pearce and Giles D. Atkinson, "Capital Theory and the Measurement of Sustainable Development: An Indicator of 'Weak' Sustainability," *Ecological Economics* 8, no. 2 (1993): 103–08, https://doi.org/10.1016/0921-8009(93)90039-9.

[53]See Gordon R. Conway and Edward B. Barbier, *After the Green Revolution: Sustainable Agriculture for Development* (London, UK: Routledge, 1990).

[54]Johan Rockström et al., "Planetary Boundaries: Exploring the Safe Operating Space for Humanity," *Ecology and Society* 14, no. 2 (2009): 32, http://www.ecologyandsociety.org/vol14/iss2/art32/, focus on carrying capacity from both an ecological and a human density point of view.

[55]Hall, "Toward a Theology of Sustainable Agriculture," included the following references: Caffey, Romaire and Avault, "The Sustainability of Crawfish Aquaculture"; Claude E. Boyd and Craig S. Tucker, "Sustainability of Channel Catfish Farming," *World Aquaculture* 26, no. 3 (1995): 45–53, both took a cautiously optimistic view; while Naylor et al., "Effect of Aquaculture on World Fish Supplies," focused on challenges to sustainability in aquaculture at that time. More recently, Claude E. Boyd et al., "Achieving Sustainable Aquaculture: Historical and Current Perspectives and Future Needs and Challenges," *Journal of the World Aquaculture Society* 51, no. 3 (2020): 578–633, https://doi.org/10.1111/jwas.12714, revisited both advances in the field and future needs and challenges toward a more sustainable aquaculture.

[56]Hall, "Toward a Theology of Sustainable Agriculture," 107.

[57]W. Dayton Roberts and Paul E. Pretiz, eds., *Down to Earth Christianity: Creation Care in Ministry* (San Jose, Costa Rica: AERDO, 1999); and Wes Jackson, Wendell Berry, and Bruce Colman, eds., *Meeting the Expectations of the Land* (Berkeley, CA: Northpoint Press, 1986).

[58]Scott Jones, "Evolution of Aquaponics," *Aquaponics Journal* 6, no. 1 (2002), https://aquaponics.com/wp-content/uploads/articles/evoluton-of-Aquaponics.pdf.

[59]C. Somerville et al., *Small-Scale Aquaponic Food Production: Integrated Fish and Plant Farming* (Washington, DC: Food and Agricultural Organization of the United Nations, 2014).

[60]FAO 2020 reveals that over 30 million metric tons of seaweeds are harvested using culture systems annually, probably reducing nutrients and helping enhance water quality in these areas.

[61]Alexander W. Geddie and Steven G. Hall, "An Introduction to Copper and Zinc Pollution in Macroalgae: For Use in Remediation and Nutritional Applications," *Journal of Applied Phycology* 31 (2019): 691–708, https://doi.org/10.1007/s10811-018-1580-5; and Geddie and Hall, "Development of a Suitability Assessment Model for the Cultivation of Intertidal Macroalgae in the United States," look at growing macroalgae for possible food or feed and optimal siting of macroalgae cultivation in the United States. Currently, most macroalgae is grown in Asia.

[62]Matthew D. Campbell and Steven G. Hall, "Hydrodynamic Effects on Oyster Aquaculture Systems: A Review," *Reviews in Aquaculture* 11, no. 3 (2019): 896–906, https://doi.org/10.1111/raq.12271, addressed oyster aquaculture and noted parallels with reef systems, and the possibilities with good design to grow more food, use less energy, and potentially enhance the environment.

[63]Daniela Sousa et al., "Self-adaptive Team of Aquatic Drones with a Communication Network for Aquaculture," in *Progress in Artificial Intelligence: 19th EPIA Conference on Artificial Intelligence, EPIA 2019, Vila Real, Portugal, September 3–6, 2019, Proceedings, Part II* (Lecture Notes in Computer Science), ed. Paulo Moura Oliveira, Paulo Novais, and Luís Paulo Reis (Cham, Switzerland: Springer, 2019), 569–80. At this conference, some presenters discussed not only communication but also various ethical issues with these vehicles.

[64]Jianhua Bao et al., "Integrated Navigation for Autonomous Underwater Vehicles in Aquaculture: A Review," *Information Processing in Agriculture* 7, no. 1 (2019): 139–51, https://doi.org/10.1016/j.inpa.2019.04.003, include use of autonomous submarines for inspecting ocean aquaculture cages.

[65]Anny Keli Aparecida Alves Cândido et al., "Water Quality and Chlorophyll Measurement through Vegetation Indices Generated from Orbital and Suborbital Images," *Water, Air, and Soil Pollution* 227 (2016): article number 224, https://doi.org/10.1007/s11270-016-2919-7 .

[66]Erich Luening, "Scientists See Role for Robots in Mariculture," *Aquaculture North America* (March 3, 2016), https://www.aquaculturenorthamerica.com/scientists-see-role-for-robots-in-mariculture-1603/, addresses this issue further; while the National Society of Professional Engineers Code of Ethics for Engineers (2019) includes an ethical code for professionals in the engineering field, https://www.nspe.org/resources/ethics/code-ethics, hereafter NSPE 2019. Discussions are ongoing as to the implications for autonomous vehicles and systems.

[67]Ingrid Bouwer Utne, Ingrid Schjølberg, and Ingunn Marie Holmen, "Reducing Risk in Aquaculture by Implementing Autonomous Systems and Integrated Operations," paper presented at the European Safety and Reliability Conference, ESREL 2015, held September 7–10, 2015, in Zurich, Switzerland, published in *Safety and Reliability of Complex Engineered Systems: ESREL 2015*, ed. Luca Podofillini et al. (London, UK: CRC Press, 2015). NTNU (Norwegian University of Science and Technology) Ocean Week 2015 held May 4–7, 2015, in Trondheim, Norway, addressed both fixed and moving automated systems, https://www.ntnu.edu/documents/919518/1262417150/Ocean+Week-program+final.pdf/5ea39bd7-7381-44a3-b3d0-0c5189fb4179.

[68]Utne et al., "Reducing Risk in Aquaculture."

[69]NSPE 2019.

[70]Sharkey, "The Ethical Frontiers of Robotics," 1801.

[71]Vashti M. Campbell, Alexander Chouljenko, and Steven G. Hall, "Depuration of Live Oysters to Reduce *Vibrio parahaemolyticus* and *Vibrio vulnificus*: A Review of Ecology and Processing Parameters," *Comprehensive Reviews in Food Science and Food Safety* 21, no. 4 (2022): 3480–506, https://doi.org/10.1111/1541-4337.12969.

[72]A. M. Larsen et al., "Temperature Effect on High Salinity Depuration of *Vibrio vulnificus* and *V. parahaemolyticus* from the Eastern Oyster (*Crassostrea virginica*),"

International Journal of Food Microbiology 192 (2015): 66–71, https://doi.org/10.1016/j.ijfoodmicro.2014.09.025.

[73]Costanza Baldisserotto et al., "Biological Aspects and Biotechnological Potential of Marine Diatoms in Relation to Different Light Regimens," *World Journal of Microbiology and Biotechnology* 35, no. 2 (2019): article number 35, https://doi.org/10.1007/s11274-019-2607-z, provide one perspective on the technological approach to value-added processing for seafood. For a more "consumer-friendly" angle, see Andy Nelson, "Demand for Value-Added Seafood Surges," *Supermarket Perimeter* (April 17, 2019), https://www.supermarketperimeter.com/articles/3465-demand-for-value-added-seafood-surges, which acknowledges that convenience foods are marketable. This may be good for the economy but provides one more area where an ethical approach is critical.

[74]Many recent and ongoing studies are focused on adding value to various biological and especially aquatic materials. Jutika Boro, Dhanapati Deka, Ashim J. Thakur, "A Review on Solid Oxide Derived from Waste Shells as Catalyst for Biodiesel Production," *Renewable and Sustainable Energy Reviews* 16, no. 1 (2012): 904–10, https://www.sciencedirect.com/science/article/abs/pii/S1364032111004618, focused on use of shells as part of more-sustainable energy production while M. Boutinguiza et al., "Biological Hydroxyapatite Obtained from Fish Bones," *Materials Science and Engineering: C* 32, no. 3 (2012): 478–86, https://doi.org/10.1016/j.msec.2011.11.021, focused on biomedical applications. Yu-Fong Huang et al., "Microwave Calcination of Waste Oyster Shells for CO_2 Capture," *Energy Procedia* 152, (2018): 1242–47, https://doi.org/10.1016/j.egypro.2018.09.176, considered how to process some of these materials to address another "grand challenge," excess carbon dioxide in the atmosphere. Each of these are at base simply "value added" (e.g., purely economic based), but actually have substantial ethical and theological implications in terms of caring for creation and wisely stewarding aquatic resources.

[75]See Matthew Morris, "Naming as a Form of Stewardship: A Case Study on Fraudulent Fishes Sold in Calgary, Alberta, Canada," *Perspectives on Science and Christian Faith* 72, no. 3 (2020): 151–66, https://www.asa3.org/ASA/PSCF/2020/PSCF9-20Morris.pdf, for a much more serious discussion of this deception.

[76]Calvin DeWitt, "Science and Ethics in Practice of Earth Stewardship," *in all things*, October 13, 2016, https://inallthings.org/science-and-ethics-in-practice-of-earth-stewardship/, addresses what he terms the "Science-Ethics-Praxis" triad. Scientists, he suggests, need to share their scientific but also ethical knowledge with practitioners. He talks about two ecosystems, each with water relations: first the desert, which has little water; and then Bald Cypress swamps, something much nearer to aquacultural work. In both instances, he notes tragic consequences of action without wisdom, and urges Christians and scientists (as well as practitioners) to share their knowledge and move toward wiser actions.