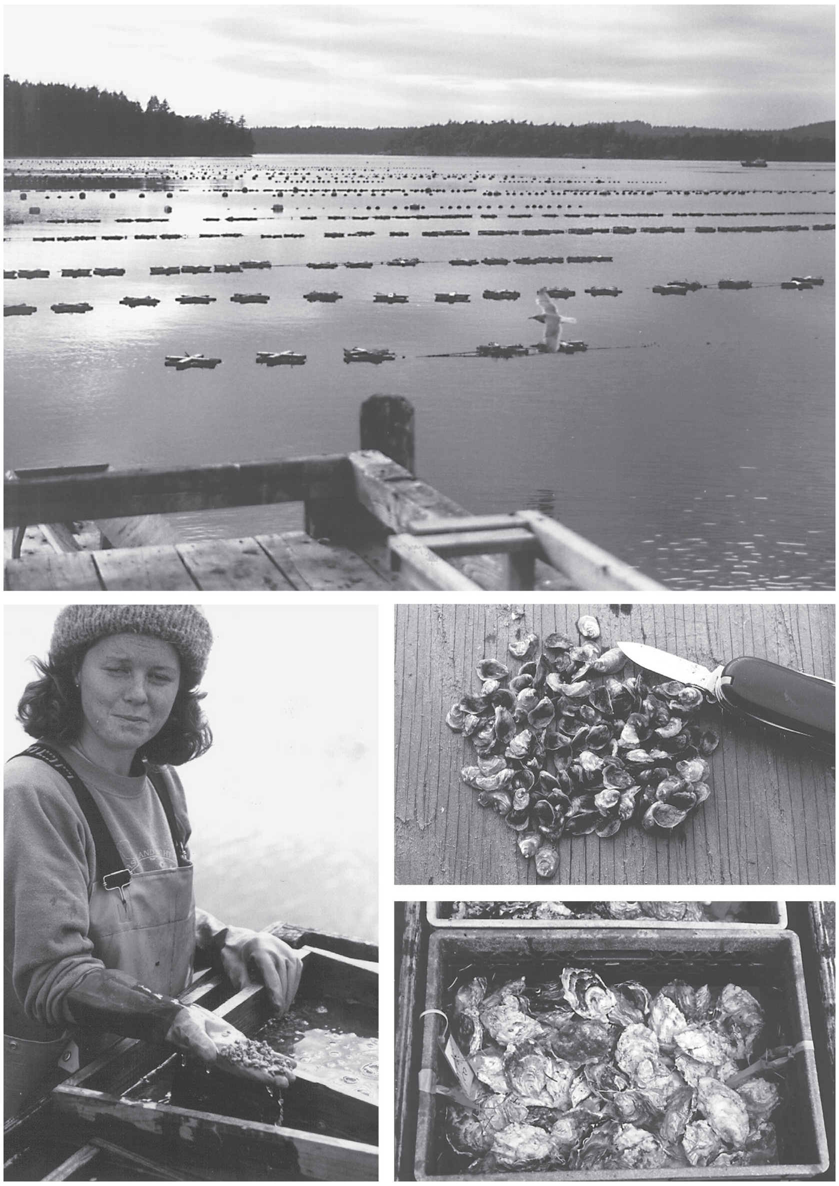


FIG. 21.19 Oysters (*Crassostrea gigas*) are cultured in racks suspended from floats in a tidally flushed bay (top) in San Juan Islands, Washington. Newly settled spat are sorted (lower left) to get the fastest-growing individuals (middle right), and these are raised in suspended plastic trays until ready for market (lower right). (Photographs by Jeffrey Levinton)

HOT TOPICS IN MARINE BIOLOGY

Shellfisheries: Which Will Fall to Ocean Acidification? 21.2

Since about 1750, approximately 337 billion metric tons of carbon have been released by the burning of fossil fuels and the manufacture of concrete. About 35.3 billion tons were released in 2013. The atmosphere's CO_2 concentration has increased from 278 parts per million in 1750, to over 400 today. As discussed in Chapter 3, the totality of this release has had profound effects on our climate, raising air and ocean temperatures in most parts of the earth, and will continue to do so. But another effect of CO_2 emissions also portends profound environmental changes. About 26 percent of all CO_2 emissions enters the ocean. In Chapter 3 we showed how this addition affects the acidity of the ocean, which will lead to areas that are undersaturated with respect to calcium carbonate skeletons—for example, the shells of bivalves, the skeletons of pteropods, and the skeletons of corals. The oceanographic community is now hard at work assessing the potential damage to marine

continues

HOT TOPICS IN MARINE BIOLOGY

Shellfisheries: Which Will Fall to Ocean Acidification? *continued* 21.2

species in the acidic ocean of the future. While pH has declined so far by a small amount on average throughout the global ocean, some marine communities are on the front lines of the threat of increasing ocean acidification.

Put simply, **upwelling systems** are at the head of the brigade of global threats from acidification. We can see this unfortunately already along the west coast of North America, where incidents of upwelling centers approaching the coast are not necessarily more frequent but appear to be more intense (Howes et al., 2015), which will exaggerate episodes of introduction of hypoxic and acidic water into the coastal zone, endangering calcifying organisms.

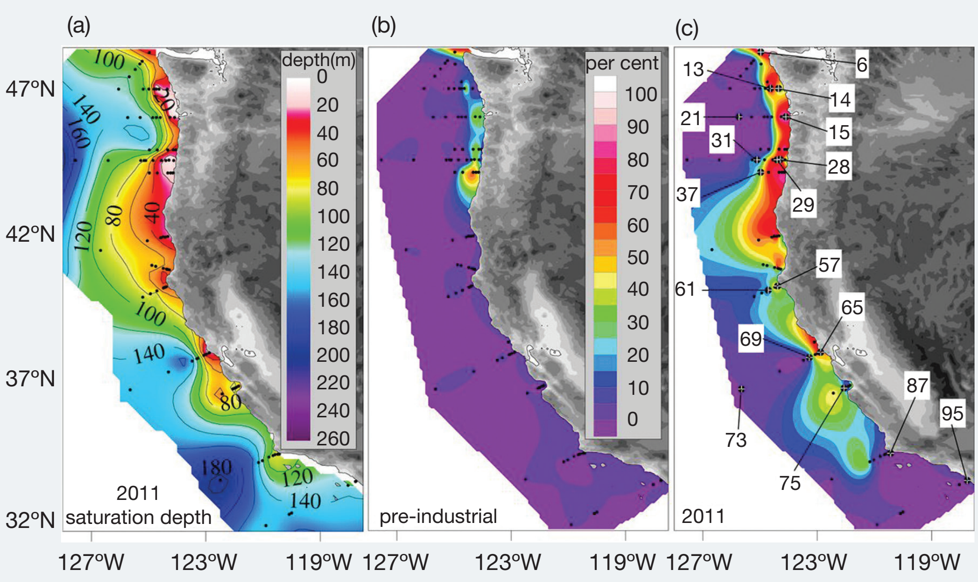
The process is fairly simple. A general zone of coastal upwelling exists along the west coast of North America from California to Alaska. The upwelling events occur every few years and may be far offshore or sometimes right over the relatively narrow continental shelf. In deep waters of upwelling systems, organic matter accumulates and oxygen levels are low because of microbial consumption of dissolved oxygen during decomposition processes. As the upwelling center approaches the coast, low-pH–low-oxygen water upwells to the surface.

The stress from upwelled water combines with an ever-increasing load of nutrients from the coastal zone, owing to inputs from populated centers and agricultural sources on the coast. The coastal input of nutrients, **eutrophication**, causes increased primary productivity, and decomposition of uneaten phytoplankton further reduces the oxygen concentration in the shallow coastal water column. Thus, we have a dual threat to calcifying organisms: acidification and low oxygen stress. But there is also an additional acidification stress in some areas, since bacteria decay uningested phytoplankton in the enriched coastal waters, producing even more CO_2 and potential acidification.

This dual stress especially has the potential to affect the larval stages of shellfish. Christopher Gobler and colleagues (2014) showed that the combination of low oxygen and high dissolved CO_2 produce both additive and interactive effects that reduce larval survival of east coast bivalves. In an east coast scallop *Argopecten irradians*, both low oxygen and low pH reduced larval survival but their combined effect was additive. But in the quahog *Mercenaria mercenaria*, early stage larvae were affected in the same way, but later stage larvae were not so affected by individual exposures to either low pH or low oxygen. In combination, however, there was some interactive effect that increased mortality. Unfortunately, it is not clear why effects are additive or interactive. Still, we can see that both low dissolved oxygen and low pH in combination are potentially harmful to larvae.

The occurrence of acidic, low-pH water is increasing along the west coast where intense upwelling is an important factor. A study by Booth and colleagues (2012) showed that episodes of intrusions by cold, low-oxygen and low-pH waters into the coastal zone have been increasing in frequency in central California. On the larger scale from California to Washington State waters, such upwelling events have very strong impact on pteropods, a major part of the zooplankton that produce shells made of aragonite. Upwelling events bring acidic water that is undersaturated with regard to aragonite, and the pteropods are frequently very damaged, with obvious evidence of shell corrosion (Bednaršek et al., 2014). Near-shore pteropods are far more damaged in frequency than those from offshore. The large California Current ecosystem has experienced a sixfold increase of undersaturated waters relative to preindustrial conditions (**Box Figure 21.4**).

Along with strong effects on the planktonic pteropods, bivalve shellfisheries in the Pacific Northwest have also been strongly impacted



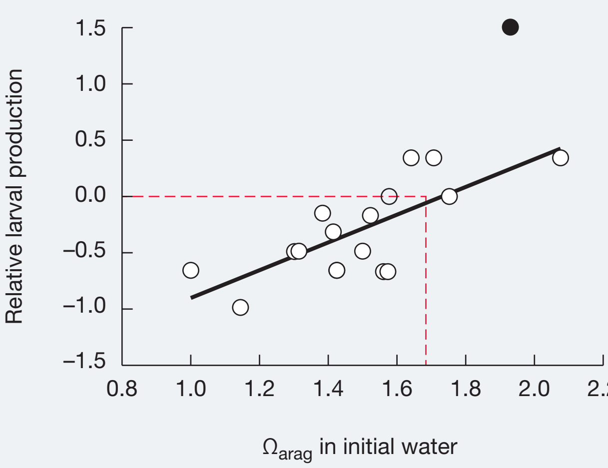
BOX FIG. 21.4 Conditions for aragonite deposition in shells off the west coast of the United States are now poor. (a) Depth of the aragonite saturation horizon. Below this depth, it should not be possible for a pteropod to make an aragonite shell. (b) Percent of the upper 100 m of the water column estimated to be undersaturated in pre-industrial times. (c) Percent of the upper 100 m of the water column estimated to be undersaturated in 2011 [same scale as in (b)]. Numbers refer to sampling localities for pteropods. (From Bednaršek et al., 2014)

HOT TOPICS IN MARINE BIOLOGY

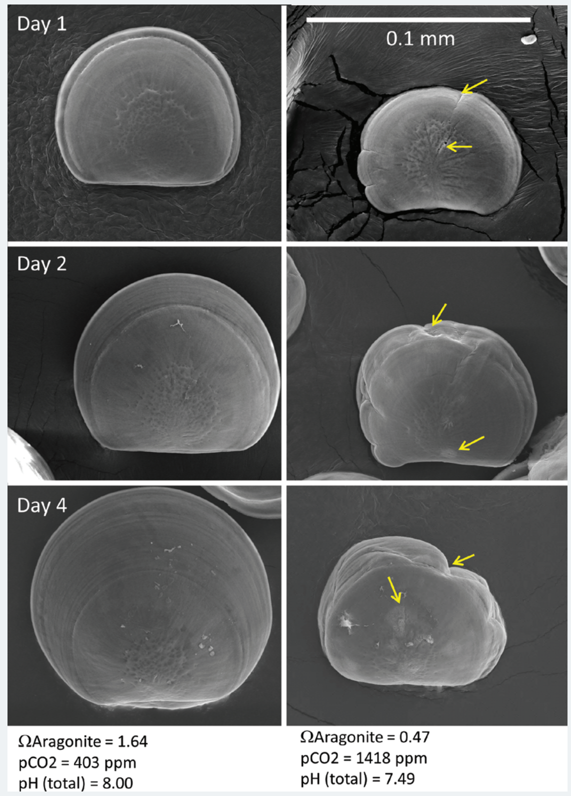
Shellfisheries: Which Will Fall to Ocean Acidification? *continued* 21.2

by these intrusions of upwelled acidic and hypoxic water. Since 2007, there have been widespread failures in hatcheries of Washington and Oregon. Most shellfish culture is of bivalves, specifically the Asian oyster *Crassostrea gigas*, the Mediterranean oyster *Mytilus galloprovincialis*, and the geoduck, *Panope generosa*. In 2009 the west coast shellfish industry earned about $270 million annually, so losses are quite worrisome. Barton and colleagues did careful studies on oyster larval growth at the Whiskey Creek, Netarts Bay, Oregon, hatchery where intrusions of upwelled water were common. In Chapter 3 we discussed the use of saturation state, or Ω, which best predicts when a mineral will be precipitated as a function of dissolved constituents. **Box Figure 21.5** shows a close positive relationship between Ω and oyster larval production rate. In another hatchery in Dabob Bay, Washington, researchers could sample from relatively saturated shallow waters and deeper, upwelled, more acidic waters and expose larvae to these different waters. Larval oyster shells of larvae placed in the deeper water samples (**Box Figure 21.6**) showed clear evidence of dissolution (Barton et al., 2015).

Upwelling events have been devastating to oyster hatcheries on the outer coasts of Washington and Oregon, but they are widespread in all coastal regions. A recent assessment (Ekstrom et al., 2015) shows that the dangers are widespread but are especially acute from the Pacific Northwest to Alaskan waters. The Alutiiq Pride Shellfish Hatchery in Seward, Alaska, is the only hatchery serving all of Alaska, with larvae of several species of bivalves, all of whose larvae are sensitive to acidification. The largest predictable changes from optimal to suboptimal values of Ω are seasonal, with extended suboptimal waters in fall and winter, when more CO_2 can dissolve into seawater, water-column respiration is elevated, and there is exposure to short-term runoff events (Evans et al., 2015). A survey of shellfish managers suggested that about half in the Pacific Northwest had experienced the effects of ocean acidification in their hatcheries (Mabardy et al., 2015).



BOX FIG. 21.5 Relative production of oyster larvae as a function of aragonite saturation state Ω. (From Barton et al., 2012)



BOX FIG. 21.6 Pacific oyster larvae from the same spawning source were placed in waters of Dabob Bay, Washington from a shallow (left column $\Omega = 1.64$) water source (left column) and deeper water ($\Omega = 0.47$) source (right column). Scanning-electron micrographs of shells show that defects develop in 1-, 2, and 4-day-old larval shells (yellow arrows). (Courtesy of George Waldbusser)

Is all hopeless? While the imminent and increasing threat of acidification is very worrisome, there are adaptive strategies used by shellfish hatchery managers that might ameliorate the threat to hatcheries, especially because older bivalves are more likely to survive transient acidification events than the larvae. Most important is monitoring, so that production of larvae and juveniles can be timed to avoid the most severe regional upwelling events. As in the case of Alaska we discussed, this may involve a seasonal adjustment to avoid the times of year when Ω is at danger levels. Some hatcheries have also used buffering strategies by adding sodium carbonate into the water, which increases the availability of carbonate ions for precipitation of calcium carbonate. In the future, shellfishery managers will have to maintain a partnership with scientists and continue to develop their own strategies to survive economically at the ever-worsening frontier of climate change.