Sustainability Profile: Ocean Acidification

Although many people are aware of the issue of climate change in the context of a warming planet, they are often less familiar with the concept of ocean acidification, even though this is a strongly related issue. We can explain the process of ocean acidification by drawing on the fundamental principles of intermolecular forces, solubility, temperature, and multiple equilibrium relationships.

Certain gases are somewhat soluble in water because of the weak intermolecular forces that allow them to associate with one another. Both oxygen and carbon dioxide gases are somewhat soluble in water.

Henry's law ($c = k \times P$) states that the solubility of a gas in a liquid (c, in units of M) is proportional to the partial pressure of the gas over the liquid (P, in atm) and the proportionality constant for that gas (k, called the Henry's law constant). One effect of Henry's law is that as the pressure of a gas over a solvent increases, the solubility of that gas increases. The Henry's law constant is specific to each gas, and it is temperature specific (it changes as temperature changes, and for a given temperature it is different for different gases). Unlike many liquids and solids, the solubility of gases decreases as temperature increases. When considering the solubility of gases, we need to know which gas we are discussing, the pressure of this gas, and the temperature.

Global temperatures are increasing. This means that not only are air temperatures increasing, but that the temperature of the ocean itself is increasing. This has an effect on the ways that ocean waters circulate because of the uneven heating of the water. The circulation patterns of ocean water alter global weather patterns, which is one implication of the term "climate change". As ocean temperatures increase, less oxygen can be dissolved in the ocean. This can lead to deoxygenation of the warmest areas, which is deadly to the marine organisms that depend upon dissolved oxygen to survive. It is important to keep in mind that these organisms represent a part of the global food chain, and their survival influences our survival.

Carbon dioxide also dissolves less in water at higher temperatures, but fossil fuel consumption and other sources of carbon dioxide are increasing. Approximately 30-40% of the carbon dioxide that is released into the atmosphere is absorbed by oceans, rivers and lakes. Increases in the amount of CO_2 in the atmosphere directly result in an increase in the partial pressure of CO_2 above ocean waters. This causes the amount of CO_2 dissolved in the ocean to increase, and this increase influences multiple aquatic equilibria processes.

When CO_2 dissolves in water, it becomes aqueous: $CO_2(g) \rightleftharpoons CO_2(aq)$

This dissolved molecule can react with water to form carbonic acid, a diprotic weak acid.

$$CO_2(aq) + H_2O(l) \rightleftharpoons H_2CO_3(aq)$$

Carbonic acid dissociates to some extent in water, losing one or both protons in this process.

Loss of first proton: $H_2CO_3(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCO_3^-(aq)$

Loss of second proton: $HCO_3^-(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + CO_3^{2-}(aq)$

These dissociations increase the amount of hydronium ion present in the waters of the ocean, and decreases the pH of the ocean. In the approximately 200 years since the industrial revolution began, the pH of the ocean has decreased by a little more than 0.1 pH units. This may not seem dramatic, but because the pH scale is logarithmic this represents approximately a 30 percent increase in hydronium ion concentration.

The solubility of slightly soluble ionic compounds can be affected by the presence of hydronium ion. If the anion of the slightly soluble compound is the anion of a weak acid, then the presence of hydronium will increase the solubility of the compound because of Le Chatelier's principle. Added hydronium ion will react with the anion to protonate it. This decreases the concentrations of the product ion of the solubility process, and causes more of the solid to dissolve.

$$CaCO_3(s) \rightleftharpoons Ca^{2+}(aq) + CO_3^{2-}(aq)$$

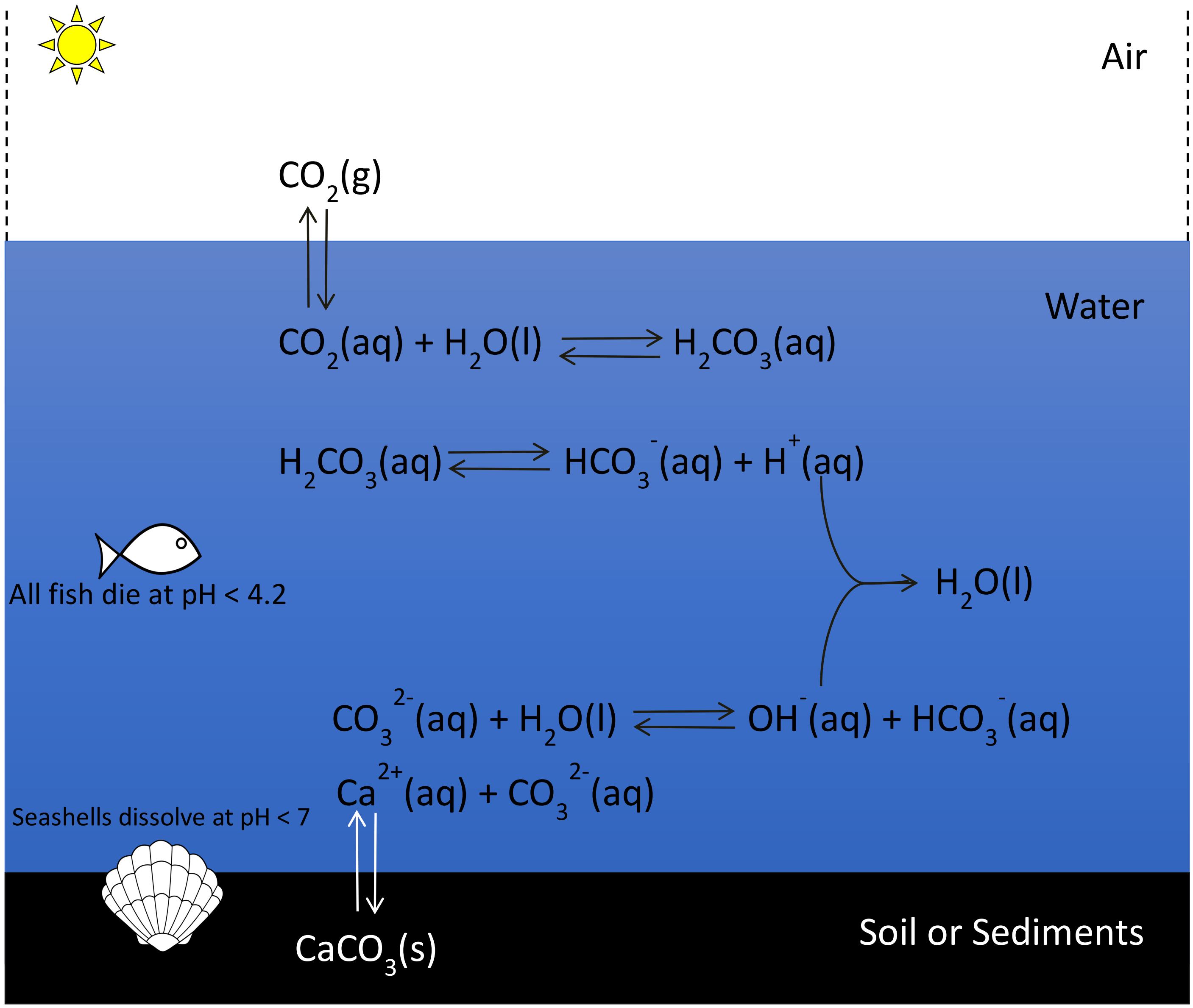
Many marine organisms make their protective shells out of calcium carbonate (and similar variations to this compound). The carbonate anion is the anion of carbonic acid, which is a weak acid. This means that carbonate can be protonated by hydronium ions, and increases the amount of calcium carbonate that dissolves. This has devasting consequences for marine organisms that make their shells out of $CaCO_3$. A decrease in pH in the ocean waters in which they live directly results in a decrease in ability to form their shells, and increases the solubility of the shells themselves once they are formed.

$$H_3O^+(aq) + CO_3^{2-}(aq) \rightleftharpoons HCO_3^-(aq) + H_2O(l)$$

For now, the pH of the ocean is approximately 8.1. This alkaline environment is becoming increasingly acidic, and is damaging the shells of oysters, corals (leading to coral bleaching), and pteropods (or "sea butterflies"). Pteropods are an important foundational species in many food webs. They are eaten by krill and whales. When placed into sea water with pH and carbonate levels projected for the year 2100, their shells dissolve slowly after 45 days. Severe shell dissolution has already been noted in pteropods in the Southern Ocean (around Antarctica). Acidification affects behaviors of other marine organisms as well, from decreasing the ability of clownfish to detect predators, or the ability of larval clownfish to locate suitable habitats.

The acidification of oceans is not an inevitable process, but it is one that will continue to lower the pH of oceans and will have consequences for marine life (and everything that depends on marine life) for as long as atmospheric levels of CO_2 are increasing or remain relatively high. Because of the interconnectedness of different environmental realms on Earth, the acidification of the oceans has been named as one of Nine Planetary boundaries of concern regarding sustaining life on our planet.

Here is a graphic created by Dr Carlos Olivo to help you visualize these complex interactions:



Questions:

Why is the amount of CO_2 dissolved in the ocean increasing?

What are the main anthropogenic (man-made) sources of CO_2?

How does dissolving CO_2 in the ocean alter the pH of ocean waters?

What effect does the increase in hydronium ion concentrations have on the solubility of calcium carbonate?

What will need to be done in order to decrease ocean acidification?

References:

https://www.noaa.gov/education/resource-collections/ocean-coasts/ocean-acidification

https://en.wikipedia.org/wiki/Ocean_acidification

https://www.stockholmresilience.org/research/planetary-boundaries/planetary-boundaries/about-the-research/the-nine-planetary-boundaries.html

Ocean Acidification Learning Objective

Describe the definition of, sources of, consequences of, and solutions to, ocean acidification.