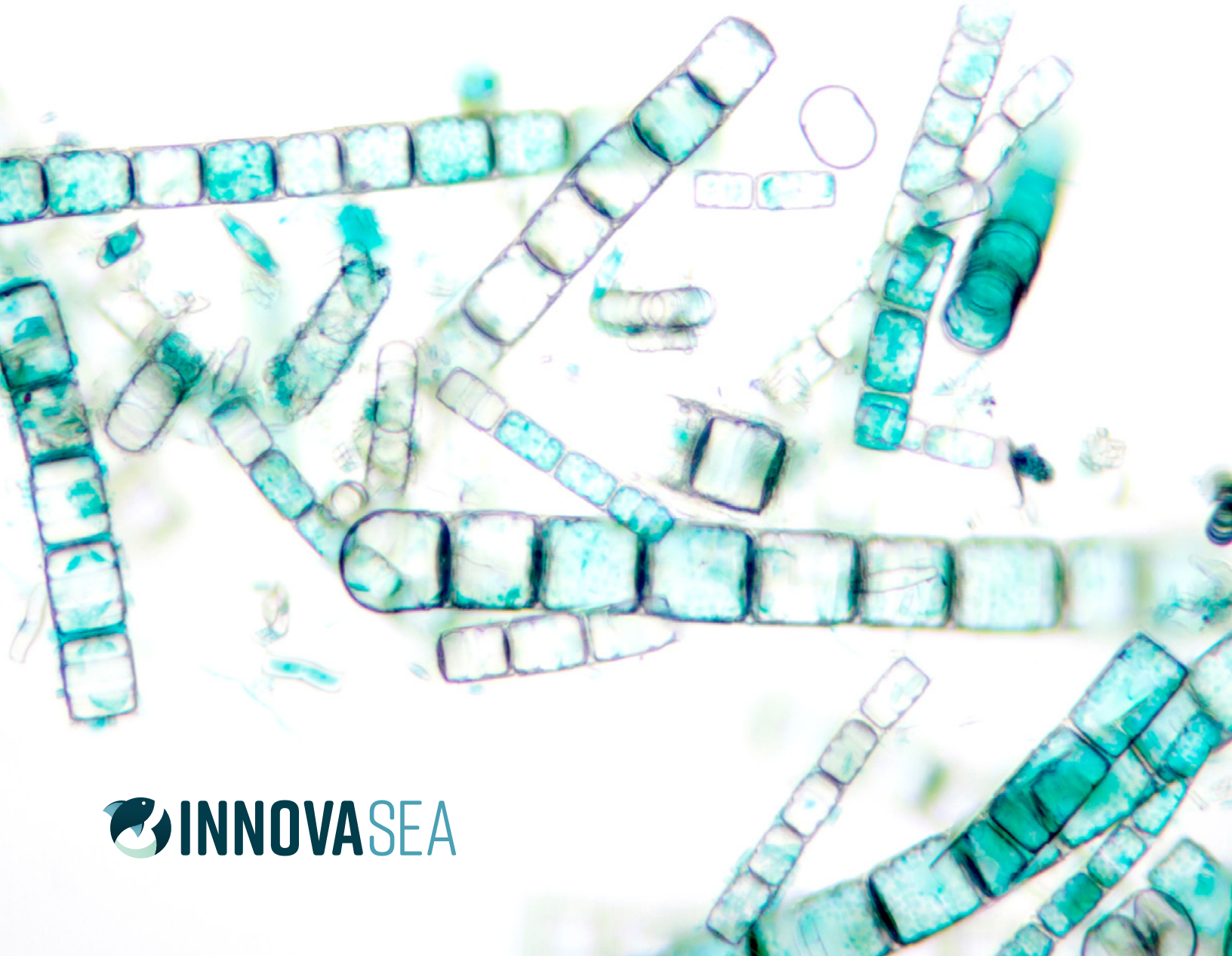
WHITE PAPER

How Light Behaves Underwater and Its Impact on Fish Farming – from Phytoplankton Growth to Salmon Development



INNOVASEA

Abstract

This white paper explains how light behaves underwater and how that affects various organisms, including phytoplankton – microscopic algae that in large concentrations can be deadly to salmon and other fish. It examines new technologies and tools that are being used to protect salmon from phytoplankton and also explores how artificial lighting can be used to prevent early maturation and preserve the health and quality of the fish.

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Part I

How Light Behaves in Water

Humans are creatures of the light. Our entire livelihood revolves around the daytime cycles dictated by Earth's exposure to the sun. As the energy source for all plants, which are the base of our food web, the sun is what allows life on Earth to flourish.

Light can be a complicated concept, but on land we have some inherent knowledge of how it works because we experience it every day. Have you ever seen the shimmering effect of light in a pool? It's a recognizable phenomenon for most, but have you ever thought about why that happens or how it works?

The physics of light in air are one thing, but what about when it passes through a new medium like water? What are the impacts on ocean life, specifically in an aquaculture setting? Having a fundamental understanding of how light works and affects a specific species is imperative when farming that species underwater.

All living things need energy. Humans and most animals get their energy from the food they eat. Plants have the unique ability to harvest light and get their energy from the sun. This is because light is a form of energy called electromagnetic radiation, and photons are the particles that light is made up of. You can think of them as little packets of energy that travel through space in waves, much like those we see at the beach. Although we cannot see the physical wave, what we can observe is the visible spectrum of light.

If we considered the entire spectrum of light, this white paper would be three times as long. So for the sake of simplicity, we will be focusing on the visible spectrum. The visible light spectrum is measured in nanometers (nm) and

ranges roughly from 380 nm to 780 nm. These numbers describe the light's **wavelength**, a key characteristic describing the distance over which a wave repeats itself. The number of waves that pass through a given point in one second is called the **frequency**. Frequency and wavelength are inversely proportional, so as wavelength increases the frequency decreases – and vice versa. The important thing to take away from this is how energy is related to frequency and wavelength. The greater the energy in a wave, the higher the frequency and the shorter the wavelength.

The Speed of Light

All light waves move through space at the speed of light, which is equal to 299,782,458 meters per second. To put that number in perspective if we consider how long it would take to fly around the world in the SR-71 Blackbird — the fastest jet in the world, capable of reaching speeds of more than 2,000 mph, it would take roughly eleven hours to complete one revolution. Traveling at the speed of light you could travel around the globe seven and a half times in a single second.

299,782,458 m/s

Speed at which light moves through space

Seven and a half

Number of times you could circle the globe in one second if traveling at the speed of light

Even though light travels at this extreme speed, it still takes around eight minutes for light to travel from the Sun to Earth's surface. Once light reaches Earth's surface, objects absorb the light based on the nature of the specific object's atoms. Atoms vibrate at specific frequencies and when they are complementary to the light frequencies they are **absorbed.** If not complementary, the light will either pass through or get **reflected**.

This phenomenon explains how we see color in objects. Let's use leaves as an example. In spring and summer when daylight and temperature are optimal, leaves are full of a pigment called **chlorophyll**. Chlorophyll is what allows plants to harvest sunlight and turn it into energy (food) to grow, more commonly known as the process of **photosynthesis**. This pigment absorbs wavelengths (colors) in the blue and red range and because they are absorbed, we do not see them. What we do see are the wavelengths or colors that are reflected, in this case green.

As summer turns to fall, growing conditions become sub-optimal. To conserve water, some plants stop producing chlorophyll. As chlorophyll breaks down into smaller molecules, other pigments such as carotenoids or anthocyanins become dominant. These pigments absorb blue and green wavelengths and reflect the beautiful yellow, red and orange colors we see in the fall.

Light in Water

Now that we have the basics down of how light works and behaves on Earth, let's add another layer and examine what happens when light hits water. We should consider ourselves lucky that air does not absorb light the way that water does. The difference between the two is what allows us to experience light levels the way we do and explains why only the surface waters of oceans and lakes are illuminated. In the ocean we consider the **photic zone** – the layer of water where sunlight reaches – to be the first 100 meters. This represents a measly 10 percent of the entire ocean, so the majority of the ocean is perpetually in minimal to zero-light conditions.

100 Meters

How deep sunlight penetrates the ocean; known as the photic zone

10%

Portion of the ocean within the photic zone

In order to measure how much light exists at any point underwater, there are four properties we must understand. First there are the inherent optical properties (IOPs), which depend only on the medium itself and what it contains – these properties are not impacted by the light source but do vary with wavelength of light.

The two fundamental IOPs are **absorption** and **scattering**. Absorption refers to how much light is converted to thermal energy when it hits an object. This is a well understood concept; we've all experienced the effects of the sun on a warm sunny day as it heats up a body of water and makes for an enjoyable beach day. Scattering refers to the amount of light that is redirected after hitting an object and further explains why objects appear a certain color. In the atmosphere, the different particles (nitrogen, oxygen, dust, water vapor, etc.) scatter blue light the most, so everywhere you look the sky appears blue.

In the ocean the strongest amount of absorption is in the green and red wavelengths of light, while blue light is scattered. This explains why the ocean appears blue. While this is true most of the time, I'm sure you have seen examples where the ocean appears green or even red. This is often the result of biological activity within the ocean.

In areas where phytoplankton exists in high concentrations, there are much higher concentrations of chlorophyll – the same pigment in leaves that gives them their green color. These pigments, which are responsible for photosynthesis, are restricted to the photic zone and can drastically change the color of surface waters in large concentrations. Other kinds of phytoplankton, such as dinoflagellates, contain different light capturing pigments that absorb

and scatter different wavelengths of light. These phytoplankton are the cause of red tides that can be extremely toxic to both humans and fish.

The second classification of optical properties we need to understand are the apparent optical properties (AOPs). AOPs depend both on the medium itself and the strength and direction of the light rays from the sun.

The first AOP is the **diffuse attenuation coefficient**, which simply describes how much light is available with respect to depth. It's easy to understand that this will both be dependent on the constituents in the water and how much light is hitting the surface (maximum light at noon on a sunny day compared to minimal light at midnight on a cloudy night). The clearer the water, the deeper the light will penetrate. If there are many particles in the water, such as dirt, sand or even phytoplankton, this will scatter the light in different directions and limit the depth the light will reach.

The second fundamental AOP is **reflectance**, which is similar to scattering except it describes a more predictable change in direction of light. Scattering changes the direction of light in multiple directions. Reflectance, on the other hand, reflects light at one predictable angle, the same angle that it hits the surface with. This is true when the surface the light hits is flat and smooth. This is the property that allows photographers to capture beautiful images reflected on calm lakes.

However, the ocean is a dynamic environment that is rarely calm. The rough surface caused by wind and waves changes the direction of a reflected ray of sunlight. This is what causes sun glitter on the water, the sparkle on the surface that you often see on a sunny day. It is the same concept that explains the shimmering light patterns we observe in a pool. These light patterns are caused by a wavy surface but unlike the ocean where we are unable to see the bottom, the light patterns are projected on the pool bottom. This is caused by a focusing effect in the wave crests and a defocusing effect in the wave troughs that continuously moves and shimmers as the small waves move around the pool.

Impact on Organisms

Light is a complicated physical concept but is critical to understand the fundamentals to know how it can impact the organisms that depend on it. How light behaves underwater has huge implications for the organisms that live there. It dictates how organisms hunt for prey, find mates and how they interact with other species.

Scientists have discovered that ocean color tells us a lot about the biological environment just below the surface, and it has been used by researchers to characterize water bodies and measure productivity on a large scale. Understanding how light interacts with water and the organisms it contains has been

extremely important in identifying biologically important areas within the ocean. And it has contributed to the development of technologies that allow us to identify and differentiate among tiny phytoplankton that are invisible to the human eye – technologies that are used daily on fish farms to monitor and manage conditions in the water.

Part II

Fluorescence

Now that we have a good understanding of the basics of how light and water interact, let's examine another principle of light called **fluorescence**. Fluorescence, from a biological standpoint, is the same concept used in fluorescent lighting, which is known for its energy-saving benefits. And although we are not concerned with the cost-saving benefits, we are interested in how fluorescent lighting works because it is the same concept utilized by sensors to measure microscopic, biological species like plankton.

71%

Percent of earth that is ocean

5%

Percent of the ocean that's been explored

Researching a population of fish has its own set of challenges. First off, they live in the ocean. Although you might think that is familiar territory because it takes up 71 percent of the Earth, its vastness means we've only actually explored about 5 percent of it. On top of that, fish are mobile, and you must be able to find the ones you wish to study – not a simple task in such a large body of water. To make it even more complicated, since fish live underwater you either need to find a way to submerge yourself or a piece of equipment long enough to make some observations.

Even with these challenges, researchers have found methods using a wide range of technology that has given us fascinating insights into some of world's most mysterious creatures. But what if the organism you want to study is so small that it's invisible to the human eye? Well if you want to study what makes up 99 percent of all biomass in the ocean, this is the problem you will encounter. The vast majority of the biomass in the entire ocean is less than .3 mm in size. To put that in perspective, a teaspoon of seawater can hold over a million different living organisms – all tiny, often single-celled.

Specifically, the ones we are concerned with are called phytoplankton. You can think of phytoplankton as the plants of the ocean.

They are the base for one of the largest food webs on the planet and produce oxygen the same way plants on land produce oxygen: by using energy from the sun and converting it to organic matter and oxygen through photosynthesis. As we mentioned earlier, the pigment in phytoplankton that enables this process is called chlorophyll. It is one of three classes of pigments (others include carotenoids and phycobilins). You will remember that pigments are part of what determines an object's color because they absorb or reflect certain wavelengths of light. It is also these pigments that allow phytoplankton to fluoresce.

1 million

Number of organisms in just a teaspoon of saltwater

What is Fluorescence?

Fluorescence is the process by which an object that has absorbed electromagnetic radiation or light re-emits that light at a longer wavelength. As mentioned earlier, a longer wavelength is indicative of a lower energy wave. This makes practical sense as some of the light energy is absorbed by the object, so the part that is re-emitted must be in a lower-energy state. More precisely, when a photon hits a molecule such as chlorophyll, the molecule absorbs that photon's energy and gets into an excited state. When the molecule relaxes, it releases the photon at lower energy and a different wavelength of light is emitted. This is the fluorescent emission or response. We've all experienced this with a black light, which is really a form of ultraviolet light. When a black light is turned on, everyone's white clothes start glowing. Normally the objects appear white, but the black light causes them to fluoresce and appear a slightly different color.

The same thing happens in the water with phytoplankton, only at a microscopic level. Different species of phytoplankton respond to different wavelengths of light. This has allowed for breakthrough discoveries that have helped scientists using fluorescent sensors determine concentrations of phytoplankton and identify concentrations of different species based solely on the pigments they contain.

Fluorescent sensors emit light at a specific wavelength and then detect the light emitted by the sample within a specific wavelength range. The intensity of the response provides an estimate for the concentration of the target

pigment. Concentrations are typically expressed in micrograms per liter (µg/L). It is important to understand how to interpret these values.

A concentration of 10 µg/L does not indicate that there are 10 individual phytoplankton per liter of water but rather how much light has returned to the sensor or relatively how much fluorescent material is present in the sample with respect to seawater. Different species contain different amounts of chlorophyll depending on the light and nutrient levels that are available to them, and even within a single species there can be differences. Phytoplankton that exist in an area with abundant light levels will contain less chlorophyll compared to those that experience overall lower light levels to maximize their ability to harness available light photons.

Generally chlorophyll concentration increases with increasing numbers of phytoplankton, but it is important to understand the relationship between the two to draw conclusions from the data. When analyzing data, it is often recommended to monitor relative changes in concentration over time instead of interpreting what specific values mean.
It is important to take water samples in the area you are studying and have a good understanding of the baseline conditions. The time of year, latitude, nutrient availability and many other factors will impact the concentrations of phytoplankton in an area.

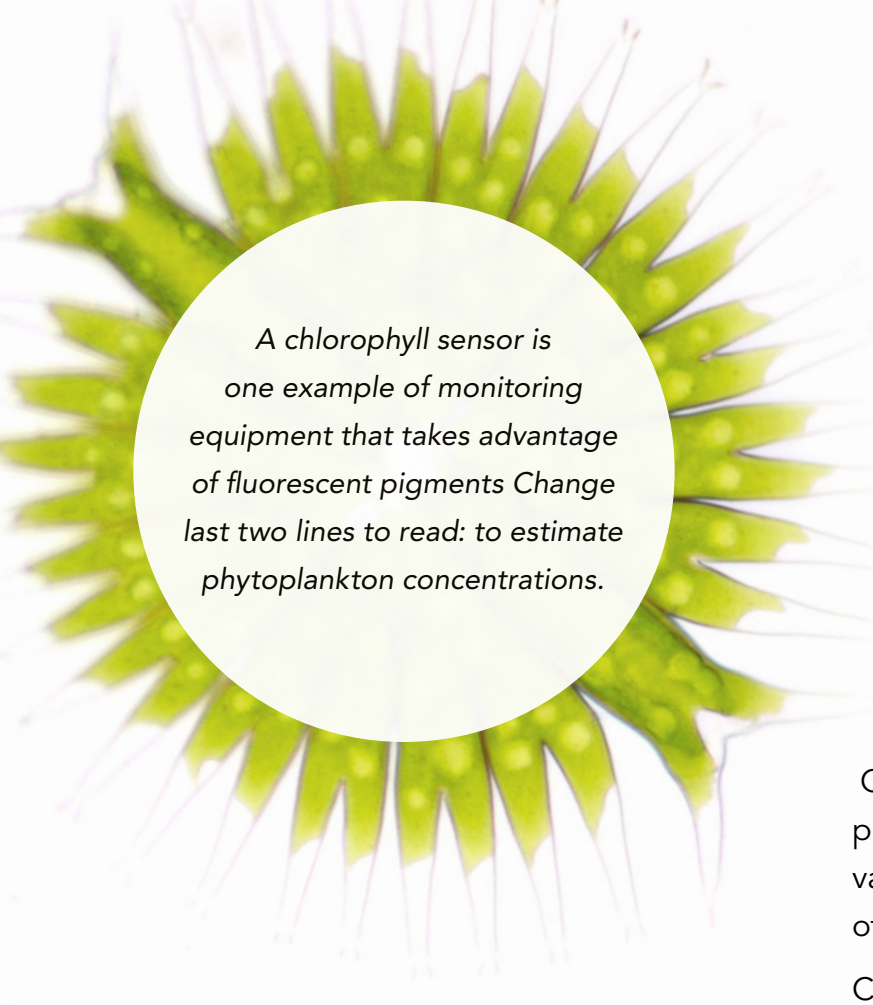
A number of factors affect phytoplankton concentrations in an area, including time of year, latitude and nutrient availability.

The Threat to Aquaculture

But why is this important in salmon farming? If phytoplankton are the base of the ocean food webs, surely the more that are present, the healthier the ecosystem?

In fact, it is quite the opposite. Salmon farmers are concerned with phytoplankton population dynamics because of the danger they pose. In large concentrations, phytoplankton can be extremely harmful to fish on an aquaculture farm. During the day, through the process of photosynthesis, they produce oxygen. But at night, in the absence of the sun, they go through respiration (the opposite of photosynthesis) and consume oxygen. Thus, in high concentrations phytoplankton can completely deplete oxygen levels in a localized area. This can cause the fish to experience prolonged periods of elevated stress and can even lead to major mortality events.

Certain species of phytoplankton can also cause health issues in a fish's gills. Fish take up oxygen by passing water over their gills, but if the water contains significant amounts of phytoplankton, this can harm the fish's ability to breathe.



A chlorophyll sensor is one example of monitoring equipment that takes advantage of fluorescent pigments Change last two lines to read: to estimate phytoplankton concentrations.

Some species of phytoplankton have spiky exteriors and can damage gills even in small concentrations. Furthermore, several species also produce toxins that can cause serious health issues for both humans and fish. At specific threshold concentrations, this can cause major mortality events on a farm, something to be avoided at all costs.

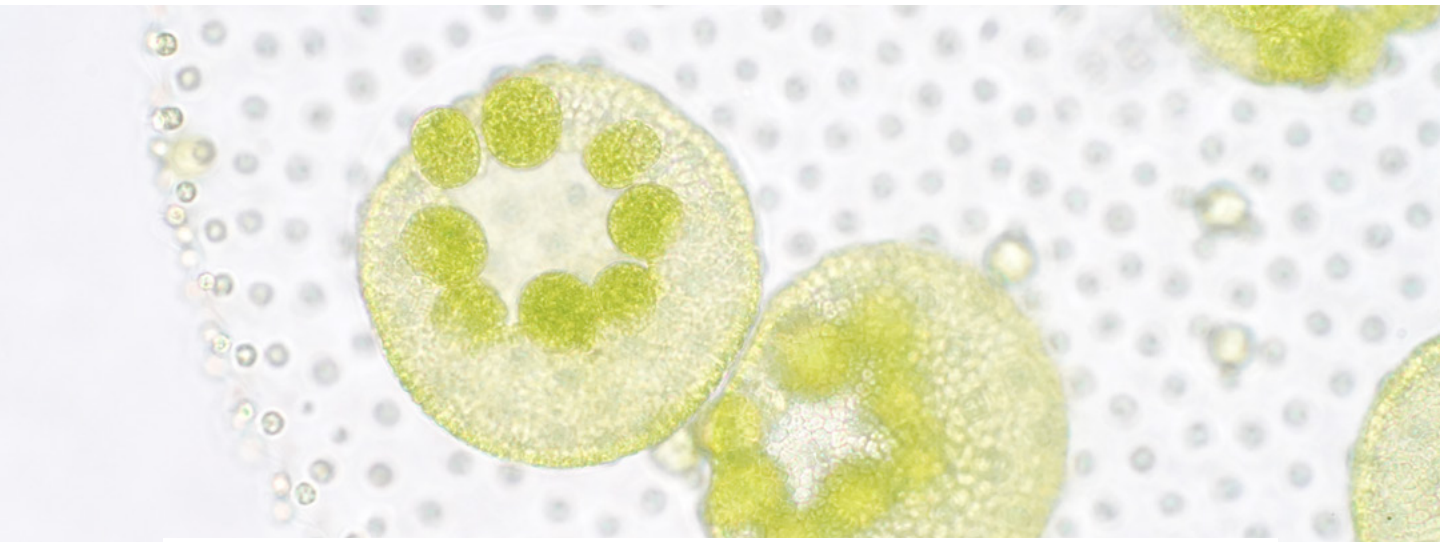
The Role of Technology

Harmful algal bloom detection and prediction has been a priority for both researchers and aquaculture farmers in recent years. There are many variables that need to be considered and, although there is no technology on the market today that can predict the occurrence or size of an imminent bloom, there are sensors that can provide valuable pieces of information. Fluorescent sensors are one type of technology that can assist salmon farmers in providing data that they can analyze to help provide insights into the conditions surrounding their farm.

A chlorophyll sensor is one example of monitoring equipment that takes advantage of fluorescent pigments to estimate chlorophyll concentrations. Chlorophyll is found in every organism that photosynthesizes, so chlorophyll sensors are valuable because they can detect the presence of any kind of phytoplankton.

Chlorophyll sensors can be deployed to monitor plankton concentrations at various depths and should be placed in strategic locations based on the surrounding hydrodynamics. Phytoplankton are at the mercy of ocean currents and tides, so monitoring should take place upstream of the farm for most informative data. In conjunction with collecting chlorophyll data, farmers take water samples to assess which species are present. They can then use sharp increases in chlorophyll concentration readings as a trigger to take these samples.

Different regions have different seasons when phytoplankton concentrations are a concern. These sensors can indicate the onset of the season, which can vary year to year. As data is collected over time, daily, monthly and seasonal



5,000
Known species of phytoplankton

300
Species known to bloom

75
Species that create harmful toxins

patterns will reveal trends and abnormalities that can inform future practices and prepare workers to be alert at the appropriate time based on historical data.

As with most things in life there are tradeoffs we must balance when we consider sensor types. The chlorophyll sensor offers great flexibility in that it can detect any organism that contains chlorophyll. However, there are at least 5,000 known species of phytoplankton, 300 of which are known to bloom and around 75 that create harmful toxins. An increase in concentration of a certain kind of species could be more alarming than another, but you must analyze a water sample to determine which species are present.

Another type of fluorescent sensor, a blue-green algae sensor, can provide farms with additional information. Blue-green algae is a type of photosynthetic bacteria that contains another fluorescent pigment called phycoerythrin. This allows the sensor to target that pigment and provide more specific information than the chlorophyll sensor.

Blue-green algae are known for producing harmful toxins, so it is important to monitor changes in their abundance over time. By pairing data from both sensors, inferences can be made regarding the proportion of blue-green algae present compared to other phytoplankton. This can assist in informing the severity level of a spike in phytoplankton

concentration. Similar to the chlorophyll sensor, collecting blue-green algae data over the long term and analyzing seasonal and inter-annual trends can provide valuable information to future site workers.

Monitoring populations of microscopic organisms has its challenges. Phytoplankton are the most abundant organisms in our oceans and their distribution and concentration depend on numerous variables. The availability of nutrients and light as well as the direction and strength of prevailing currents and tides impact how quickly blooms can form and disperse through the water column.

In 2019 an algae bloom in Norway caused the death of 10,000 tonnes of farmed salmon valued at $70 million (US). Losses of this magnitude can cripple smaller, independent farms and create significant biological waste. These events are unpredictable, but we know certain factors aggravate blooms and we can monitor changes in concentration of plankton to identify potential bloom events. Monitoring technologies are improving and provide famers with advanced methods to care for their stock.

As aquaculture transforms into a big-data industry, farmers will have more sophisticated tools to help them make decisions in real-time and compile and analyze historical data to implement precautions in future years. We may not be able to see these microscopic phytoplankton, but they make their presence known in a big way. Fortunately, sensing technology provides us with invaluable insights into their complicated life cycles.

Part III

Underwater lighting

When you walk into a room, one of the first things you notice – whether consciously or not – is how well-lit that room is. If it's a dark room, the first thing you do is turn on the light. If you walk outside and it's sunny you might put on sunglasses to protect your eyes.

There are many kinds of lights used for a multitude reasons. In our homes we use LED, fluorescent and incandescent bulbs. Each provides light, but all give off different *kinds* of light that can give rooms a different feel. Consider how well-lit bathrooms are compared to the kind of lighting you might find in a casual restaurant setting. What causes these different kinds of light? How do different kinds of light impact our mood or our sleep cycles?

Aquaculture farmers go through a similar process to homeowners when choosing lights for their fish. They must consider the cost, what type of lights to use, at what intensity and how much power they will require. Why do aquaculture farms need light? We'll answer that, but first we need to understand the complicated lifecycle of salmon and the role that light plays.

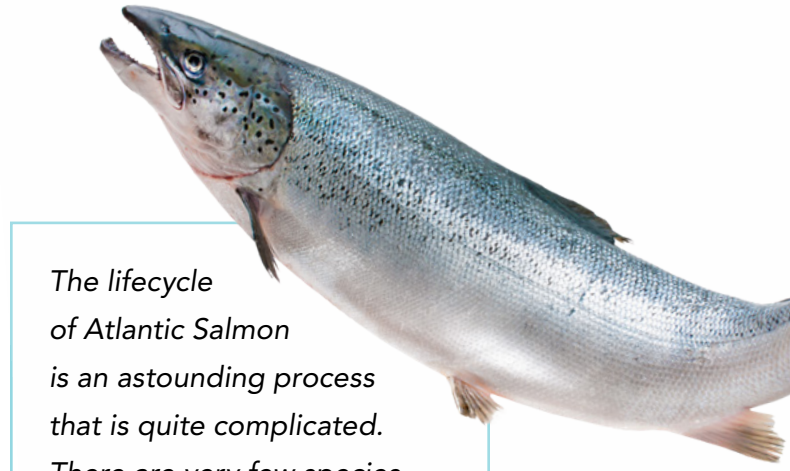
A Complex Maturation Process

The lifecycle of Atlantic Salmon is an astounding process that is quite complicated. There are very few species that are adapted to live in both freshwater and saltwater. But those that do are called anadromous or catadromous species, depending on whether they spend most of their life in freshwater or saltwater. Salmon are anadromous and spend most of their adult life at sea and return to fresh water to spawn.

In the late autumn and early winter, eggs are deposited in a hollow in a freshwater river. Fertilized eggs hatch into alevin, which then grow into fry. Fry feed on insects and other small invertebrates until they are roughly 5 to 8 centimeters, at which point they mature into parr.

Parr are recognizable by the unique markings they develop on their sides, which are often referred to as their "thumbprint." In cold northern climates the parr stage can last up to eight years. In milder climates the parr stage lasts from 1-3 years. During this time, parr go through the smoltification process where they metamorphose into smolt. This process is key as it adapts the fish for the next stage of its life where it will live at sea.

It is not by coincidence that parrs go through the smoltification process just in time to return to sea in the spring and summer. Nor is it a coincidence that they return to their natal rivers to spawn in the late fall and early winter. It has been demonstrated that both smoltification and development of reproductive organs are regulated by production of melatonin.



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Melatonin is a hormone produced by the pineal gland that is found in almost all vertebrates. Melatonin is known for regulating the sleep cycle in humans by the suprachiasmatic nucleus (SCN) in the brain. As different light levels are perceived by the SCN, it tells the pineal gland whether to release melatonin in the evening, which makes you feel sleepy, or to block production during the day.

In fish, the pineal gland is responsible for regulating melatonin levels and it is sensitive only to light. It is for this exact reason why all parrs in a similar region go through the smoltification stage at similar times – because they are all experiencing the same photoperiod (daily light cycle). The annual photoperiod is acknowledged as the key environmental cue synchronizing the reproductive cycle of salmonids to the annual calendar-time.

Farmed Salmon

When Atlantic salmon are grown in an aquaculture setting, their life cycle is slightly different. Up until the fish reach the smolt stage, they are grown in a hatchery. When they reach a certain size, they are ready to be transferred to net pens in the ocean, ideally in the spring. Salmon mature at different times depending on the region they are grown in because higher temperatures promote faster growth.

However, in an aquaculture setting farmers want to ensure they harvest before maturation. Maturation in salmon leads to different feeding patterns, an increase in pathogen susceptibility and deterioration of flesh and skin color quality. Energy from food intake is redirected from growing and used for gonad production. All these deleterious effects decrease the value of the final product and cause stress to the fish. If fish mature while in sea pens their capability to hyper-osmoregulate decreases as they prepare to return to rivers to spawn. For these reasons farmers either need to harvest prior to this process or delay maturation until fish are of market size.

There are two main strategies to delay maturation: restricted feeding during certain seasons and light manipulation. Restricting feeding in the spring can provide a physiological signal to the fish to delay maturation. However, this method reduces the amount of feed the fish are getting and slows the growth timeline, which is generally undesirable.

The alternative method is underwater lighting to manipulate the photoperiod. Underwater lights are deployed throughout cages and provide constant light overnight to inhibit the maturation process. This allows farmers to feed at normal rates while ensuring fish do not begin the maturation process.

Lighting Considerations

Aquaculture producers invest in underwater lighting systems to employ a continuous artificial light regimen to their fish during the winter of the second year at sea. But not all light is created equal, and there are considerations to be made when deciding what kind to use. In essence, water is a filter that alters the light quality and intensity. As we have learned, different wavelengths of light travel through the water more efficiently than others, so it is important to consider the intensity of light that the fish are experiencing.

Certain thresholds exist that determine the minimum intensity that will delay maturation without providing too much light that results in wasted energy. Determining the number and type of lights required and the position to deploy them is one of the core challenges of providing the appropriate light intensity.

Producers would not only benefit financially but maximize their ability to achieve the desired effects by understanding both the intensity (quantity) and spectral composition or wavelength (quality) of light they are providing.

A 2011 study comparing lighting systems in aquaculture by Leclerq et al.[1] came to the following conclusions:

- Across different lighting systems, melatonin production and maturation rate decreased proportionally to increased light intensity.
- Excessively high light intensity can induce an acute stress response.
- *In vitro,* red light (ƛ 650 nm) is less efficient at suppressing melatonin production in Atlantic Salmon when compared to blue (ƛ 450 nm) and green (ƛ 550 nm) light.
- In Atlantic Salmon the light threshold to suppress melatonin production to daytime levels is considered to be 0.016 W $m^{-2.}$

These findings help provide some baseline information to help farmers in choosing appropriate lighting systems and the best options may vary from site to site. Farmers need to consider the size of their pens, the turbidity of the water and the composition of particles to determine the effectiveness of different lighting systems. Producers have the ability to test different systems and use light sensors to measure if their lights are producing the desired effects.

Conclusion

Light is a complicated concept, but understanding its fundamentals is vital for anyone in the aquaculture industry. Light is the reason life flourishes on land and in our oceans, and we would be lost (both literally and metaphorically) without it. Understanding the basics can empower aquaculture farmers to make informed operational decisions that improve farm efficiency and promote fish welfare.

Aquaculture producers are constantly improving practices and using new technology to improve operations. It's an ongoing challenge, but as the inventor of the light bulb, Thomas Edison, once said, "I have not failed. I've just found 10,000 ways that won't work."

1. Leclercq, E., Taylor, J. F., Sprague, M. & Migaud, H. The potential of alternative lighting-systems to suppress pre-harvest sexual maturation of 1+ Atlantic salmon (Salmo salar) post-smolts reared in commercial sea-cages. Aquacultural Engineering 44, 35–47 (2011).

About the Author

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About Innovasea

Fueled by leading-edge technology and a passion for research and development, Innovasea is revolutionizing aquaculture and advancing the science of fish tracking to make our oceans and freshwater ecosystems sustainable for future generations. With 250 employees worldwide, we provide full end-to-end solutions for fish farming and aquatic species research – including quality equipment that's efficient and built to last, expert consulting services, and innovative platforms and products that deliver unrivaled data, information and insights.

To learn more about Innovasea's environmental monitoring solutions, visit **Innovasea.com/aquaculture-intelligence**.

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