Light as a Limiting Factor for Aquatic Animals and Plants

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Every school boy knows that light is required for the growth of green plants and that all animals, including ourselves, are dependent directly or indirectly upon the plants for their food supply. It is not so obvious, however, that exactly the same situation is encountered in the aquatic habitat. The ultimate source of energy for all the multifarious life in the sea and in every body of fresh water is sunlight. Furthermore most fish and many types of animals need enough illumination to see—at least part of the time—to catch their food and to avoid being caught themselves. But light does not penetrate into water indefinitely: it is absorbed by the water itself and further reduced by sediment and by stains. The aquatic biologist is thus concerned to know how much light exists at various depths in rivers, ponds, lakes and in the ocean itself, and what are the maximum depths at which fish can see and at which the all-important green plant can make a living.

Since no natural body of water can be any more transparent than pure water itself, let us begin our study of the biological action of light in the aquatic habitat by imagining a lake full of distilled water. The penetration of sunlight into such a lake is represented diagramatically in Figure 1. Depth is indicated along the right hand side of the graph with the surface at the top. At the upper right hand corner of the figure the full (100%) intensity of the sunlight is indicated and

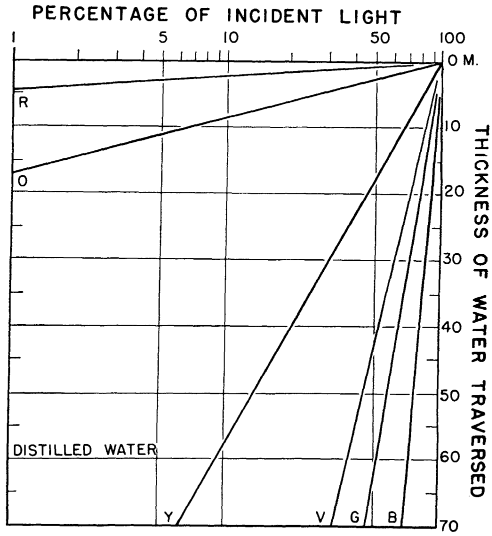

FIGURE 1. Transmission of light by distilled water at six wavelengths within the visible spectrum. Curves show the percentage of incident light (logarithmic scale) which would remain after passing through the indicated thickness of water.

Color	*Wavelength*	*Absorption/meter*
Red	7200 A	64.5%
Orange	6200	23.5
Yellow	5600	3.9
Green	5100	1.1
Blue	4600	0.52
Violet	3900	1.63

diminishing percentages are found toward the left. As we descend into our hypothetical lake the illumination is progressively reduced in intensity, but the *rate* of the diminution is expressed by the slope of the line and this is very different in the various parts of the spectrum. Thus the rate of absorption of the red

(R) element in sunlight is seen to be very high, that for yellow light (Y) lower, and that for blue light (B) very much lower. For example, after traversing 70 meters (about 70 yards) of distilled water blue light has suffered only a slight reduction —to 70% of its initial value, whereas yellow light has been reduced to 6%. In the case of red light a reduction to 6% had already taken place after passing through less than 3 m. of water. There curves represent the uppermost limit possible for the transparency of any body of water.

Now the energy of the sun as it reaches the earth's surface is not equal in all parts of the spectrum but is distributed as shown by the uppermost curve in Figure 2. In this diagram the various colors which make up sunlight are represented along the baseline and the height of the curve is proportional to the intensity of each spectral region. We see that the greatest intensity occurs in the blue-green, that a relatively small amount of energy remains when the ultra-violet is reached, but a considerable amount still exists where the red merges with the infra-red at the extreme right. We therefore start with unequal quantities of energy at the different wavelengths and these are absorbed at unequal rates as the light penetrates into the water. The result is that after passing through successive meters of water the nature of the daylight present becomes rapidly and profoundly altered, as is indicated by the change in the shape of the curves in Figure 2 representing depths down to 100 m. As a consequence after sunlight has traversed 100 m. of distilled water nothing but the blue component of daylight with a little green and violet remains.

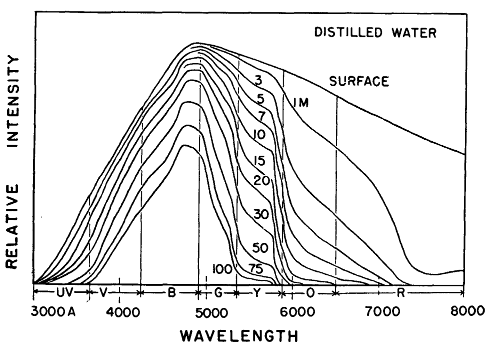

FIGURE 2. The spectral distribution of solar energy at the earth's surface is given by the uppermost curve. When sunlight is passed through successive meters of pure (distilled) water, the reduction of intensity and the change in spectral distribution which result are indicated by the curves beneath. (Courtesy of Dr. E. A. Birge.)

This selective action of the water on sunlight accounts in part for the color which one sees when one looks down into any natural body of water. In the Caribbean or the Sargasso Sea, for example, the water is so very clear that light penetrates to a considerable depth before it is reflected back up to the eye. When the rays emerge, they have been stripped of all parts of the spectrum except the blue. In less transparent water the light does not travel so far before it returns to the surface and hence more of the green and yellow components still remain. In more turbid water suspended particles may themselves appreciably affect the color of the water and in ponds and streams stains are often present which render the water orange or even red.

If we wish to compare the transparencies of different natural waters, it is obvious that we must consider the same part of the spectrum in each case. In Figure 3 the penetration of the central, or yellow-green, region of the spectrum into various typical natural waters is shown. The rates of absorption which these lines represent are taken from actual measurements made in the field by investigation all over the world.

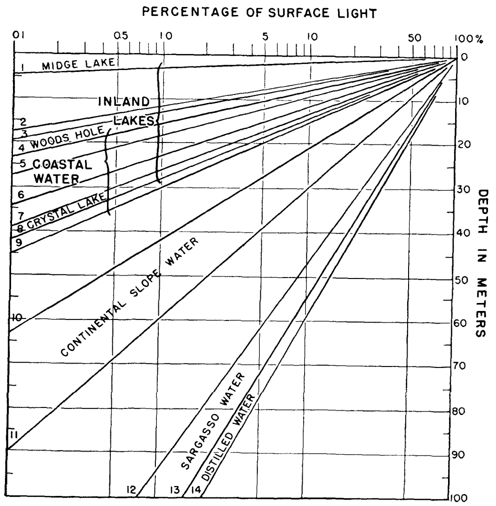

FIGURE 3. Comparison of the rates of penetration of the yellow-green component of daylight into natural waters. Curves show the relation between depth and illumination expressed as a percentage of the light at the surface. (Logarithmic scale.)

Curve	*Location*	*Absorption per meter*
		%
1.	Midge Lake, Wisconsin	78
2.	Trout Lake, Wisconsin	33
3.	Gunflint Lake, Minnesota	30
4.	Woods Hole Harbor	26
5.	Thatcher Pass, San Juan Islands	23
	Buzzards Bay	22
6.	Vineyard Sound	18
7.	Baltic Sea	16
8.	Crystal Lake, Wisconsin	15
9.	English Channel	14
10.	Gulf of Maine (deep basin)	10
11.	Off Vancouver Island	7.6
	Continental Slope, s. of Nantucket Shoals	7.2
12.	Gulf Stream	5.0
13.	Cayman Sea (Caribbean)	4.1
14.	Distilled water	3.8

One observes that the water in the Sargasso Sea is nearly as transparent as distilled water. The illumination, of course, does not come to an abrupt end at any depth: it continues downward indefinitely, but ever diminishing. A convenient way to compare the transparencies of different areas is to state the depths at which the light intensity is reduced to 1% of its value at the surface. Thus in the Sargasso region we see that light can penetrate to 100 meters or more before a reduction to 1% has occurred. Beyond the edge of the Continental Shelf 100 miles or more from the coast in both the Atlantic and the Pacific the transparency is such that the 1% value is reached at about 50 meters. In coastal waters the same value occurs at between 30 m. and 15 m. Although there are a few inland lakes which are as clear as typical coastal waters, the majority of them are more turbid. In Midge Lake, Wisconsin, for example, the illumination has been reduced to 1% of its surface value at 3 m. The extreme range of possible transparency in natural waters is thus very great, and consequently the amount of daylight at any given depth differs tremendously in different cases.

How much light do fish require to see? The fresh-water sunfish has been made to answer this question by a clever experiment which involved moving a series of stripes across the glass side of its aquarium under diminishing illumination. If the sunfish sees a movement of the background, it responds by swimming in the opposite direction. (Its ancestors found this reflex to the apparent movement of the river bottom a useful way to avoid being carried down stream.) When the illumination becomes so weak that the stripes are no longer visible, the sunfish no longer executes its characteristic response. At this point the light intensity was found to be equal to .000,000,000,1 (or 10^{-10}) of full noon sunlight. This is approximately the same as the limit of human vision.

We may now proceed to calculate at what depths such a minimum illumination is to be found. From Figure 3 it appears that in the Sargasso Sea the light is reduced to 0.1 by each 50 m. of water. Fish are therefore still able to see small objects at a depth of 500 m. (10×50 m.) in this part of the ocean. Although the difference between light and dark may be perceptible for still another 500 m., we can definitely state that below 1000 m. (about half a mile) night is perpetual. On Georges Bank off Cape Cod the maximum depth for vision is about 180 m. But here, since the water is only some 60 m. deep, vision would easily be possible at the bottom. And a similar conclusion is reached in the case of other coastal regions. As for fresh water we find that the limit of vision would occur at 110 meters in the clearest lake where measurements have been made (Crystal Lake, Wisconsin), and 28 m. in a very turbid lake (Adelaid Lake, Wis.), and at 70 m. in a deep lake (Gunflint Lake, Wis.), but in every case the bottom occurs at a lesser depth. Fish can see, then, in every part of the lake, at least during the middle part of the day.

Plants require much more light than the minimum needed for the vision of fish. The result is that plant life is limited to the upper strata of the sea and of deep lakes, whereas animals can range to all depths. In fact, many types of fish, crustacea, and other animals have been captured in nets trawled over the bottom of the ocean at a depth of three miles or more. These animals apparently are able to get along without any illumination—unless, indeed, they make use of each other's luminescence. But even the animals groping about on the floor of the ocean miles beneath the zone of plant life are dependent in the last analysis upon the energy of sunlight stored in the green plant through the process of photosynthesis. Either the plants themselves die and sink down, or are eaten by animals which later descend to the depths and fall prey to the bottom fauna.

The lower limits at which plants are found growing on the bottom will obviously vary very widely according to the transparency. In the Baltic Sea the greatest depth for plant growth is 20 m. and off Iceland it is 50 m., whereas in the Mediterranean the limit may not be reached short of 160 m. In a lake of average transparency such as Trout Lake, Wisconsin, fixed plants are never found deeper than 12 m.

The plants which are rooted in the bottom constitute only a small part of the total vegetation of the ocean or of a lake. A much greater bulk consists of the floating plants such as the blue-green algae and the diatoms which are unicellular and therefore microscopic in size. These exist in every body of water and sometimes are found in very great abundance.

It is relatively easy to determine experimentally the light requirements of these tiny plants, for water containing them can be poured into bottles and suspended by a rope from a buoy at any desired depth in a lake or in the ocean. The rate at which the process of photosynthesis goes on can then be judged by measuring the amount of oxygen which is evolved by the plants within a known interval of time. From a series of such hanging bottle experiments one may ascertain the greatest depth at which any appreciable photosynthesis is taking place. But this is only half the story. Every living plant must respire and this means the consumption of oxygen. The destructive metabolic process represented by respiration is going on at the same time as the up-building process of photosynthesis and, in order for the plant to maintain itself and to grow, the latter must go forward at a faster rate than the former. The depth at which the illumination is sufficient to allow photosynthesis just to balance respiration is termed the *compensation point.* Although some photosynthesis may be going on below this level, the plants at greater depths are fighting a losing battle and will eventually die. The lessened intensity of light will not enable the storage of energy to take place as fast as the respiration of the plant requires. The compensation point during the middle of the day in the Sargasso Sea probably occurs at a depth greater than 100 m.; in the English Channel it has been located at 45 m., in Woods Hole Harbor at 7 m., and in Trout Lake at about 12 m.

The plant is under a further disadvantage in that respiration proceeds continuously but photosynthesis can go on only during the daylight hours. Accordingly the plant must manufacture enough food while the sun is up to tide it over the rest of the 24 hours. From the point of view of the continued growth of the plant the really significant value is the depth of the compensation point over the whole 24 hour period. The depth at which photosynthesis is just sufficient on this basis will be much less but the exact level has not yet been measured in any lake. In a Scottish estuary the compensation point was found to vary from 2 m. to 30 m. according to the season. The organic matter built up by the green plants in this very thin stratum at the surface is therefore the entire ultimate source of energy for the whole of the depth of the water beneath it.

Of all the light which falls upon the surface of a lake it has been calculated that only from 1½% to 14% is absorbed by the plants suspended in the water. The efficiency of photosynthesis, *i.e.,* the process of converting the radiant energy absorbed by the plant into the potential energy of the carbohydrate formed—under natural conditions is somewhat less than 3%. When the two factors are taken together we obtain an over-all efficiency of production ranging roughly from .04% to .4%. The efficiency with which aquatic algae manufacture carbohydrate is therefore only a small fraction of a per cent. It thus appears that most of the light incident on the surface of lakes or oceanic areas is absorbed by the water itself or by sediment and stains, and that only a very small part of it can be utilized by plants or animals. We conclude that aquatic organisms are existing under very unfavorable circumstances in regard to the utilization of solar energy. It is for this reason that light is so frequently found to be a limiting or a highly significant factor in the aquatic environment.

PROGRAM SUGGESTIONS

To aid in the construction of interesting and valuable programs for local Biology Teachers Associations, the National Secretary is preparing a booklet of programs that have been held in various local associations.

At present the booklet contains the programs of the last ten annual meetings of the Illinois Biology Teachers Association and a few other suggestions. Any member of our association who is preparing programs for local meetings may borrow this booklet for a limited time. Send requests to Mr. P. K. Houdek, Secretary-Treasurer, Robinson, Illinois.