
QUANTIFYING THE SEVERITY OF HYPOXIC EFFECTS

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We want to emphasize that quantitative assessments of hypoxia can be carried further than they have been. This requires more useful quantification of hypoxic effects and, through collaboration between scientists and decision-makers, explicit interpretation of these effects. We believe that one or more formal indices of hypoxic effects can help structure these improvements to better define and assess hypoxic effects.

Assessment of hypoxia entails three elements:

1. Knowledge of dissolved oxygen concentration (DO) fields, generally through measurement.

2. Knowledge of DO dynamics, to understand what could be done about hypoxia.

3. Knowledge of hypoxic effects and their social importance, to help decide if anything need be done.

In the Chesapeake, progress is being made in understanding the DO fields and their dynamics. However, there appears to be little quantitative understanding. Bay-wide, of socially consequential effects of hypoxia (e.g., how much hypoxia limits oyster or soft shell clam production). This lack of quantitative understanding is marked, even to the extent of disparate professional views as to which effects are most important. We argue that it is important and relatively easy to quantify the severity of at least some
socially consequential effects; we use mortality in oysters as an illustration. Before indexing other effects (e.g., avoidance behavior and its population consequences in striped bass and blue crabs, or growth reduction in oysters), additional research may well be necessary to determine the social significance of these effects or even how to quantify them.

Further, if we are to really "help decide if anything need be done" we must go beyond simply quantifying effects. We must help interpret them. We must help decision makers determine how much hypoxia is acceptable. Only when governments have defined unacceptable hypoxic effects quantitatively can they establish defensible goals with regard to hypoxia.

With the help of other investigators we have developed an index of hypoxic effects primarily for decision making purposes. First we need a readily understandable scale for the index. We use the same scale used for other indices in a series designed to quantify several marine pollution effects (Figure 1).

The index scale has three ranges:

0-1  no concern

1-10  warning range (justifies consideration, if "enough area" is affected)

>10  alarm range (justifies action, if "enough area" is affected)

For illustrative purposes, assume the index value of 10 corresponds to 10% hypoxic-induced adult oyster mortality over a summer season. In practice the lower boundary of the alarm range would be negotiated by the parties concerned, and decided upon by the appropriate decision makers.

Note that the index does not address how much area must be affected to justify governmental consideration or action. This undoubtedly varies greatly from region to region, and we doubt that it can be usefully defined by an algorithm.

Now we can quantify hypoxic-induced mortality and help interpret it for decision making.

When DO falls below a threshold value, depending on temperature, an oxygen deficit begins to build up in the oyster. A low dissolved oxygen episode is defined to occur during the time period when the DO is consistently below this curve, i.e., when oysters are accumulating oxygen debt. We want to index the accumulation of this oxygen debt as the episode progresses. In order to calculate the index for an hypoxic episode we need three things:

1. Bottom DO and temperature measurements over the episode, measured frequently enough to allow meaningful estimates,

2. Authoritative judgment that some percentage of hypoxic-induced oyster mortality is unacceptable. (Other endpoints might be chosen; it is important that they be estimable endpoints that are important for environmental decisions. For instance, we could judge that some percent of larval oyster mortality is unacceptable. This might well be a more sensitive measure than adult mortality, as has been suggested by some experienced investigators.)

3. Finally, we need some quantitative linkage between the DO field and the resulting oyster mortality.

It is not a major problem to measure the DO field in Chesapeake Bay — not trivial or cheap, but it is more straightforward than other information and decisions needed to assess hypoxic effects.

Let's assume we have an authoritative judgment about unacceptable effects, for example, that 10% oyster morality due to low DO is socially unacceptable. Now, in principle, we could link DO to oyster mortality in either of two
ways: either by field observations or from the measured DO concentration and reliable dose/response relationships estimated in the laboratory, i.e., by determining what dose of oxygen deficit causes 10% mortality. It would be very difficult and very costly to reliably link DO to field estimates of oyster mortality, at least over the entire Bay, so we chose to use laboratory estimates of 10% mortality as functions of DO, temperature and exposure duration. We emphasize that existing dose response data for the oyster are not reliable enough to index all relevant conditions in the Bay. But these data are relatively easy and inexpensive to get.

We have used laboratory dose response data from Bill Stickle, Louisiana State University. We can use Stickle's LC10 estimates to determine what environmental conditions will cause an oxygen deficit to build up, and how long it will take to kill 10% of the oysters (Figure 2). The highest concentration of oxygen at a given temperature that causes O2 deficit is termed the "incipient lethal" DO concentration. Incipient lethal concentrations are specified by the vertical asymptotes of the LC10 curve of Figure 2. These concentrations are plotted in Figure 3. In practice, the curves of Figure 2 should be fitted statistically. A four-parameter hyperbola seems to provide the best fit to this unusually variable family of curves, based upon several data sets for fishes and invertebrates.) Once these things are known then we can calculate the index at each station sampled. Each index value is the sum of daily doses of oxygen deficit:

$$\text{Index} = \Sigma \left( \text{daily dose of oxygen deficit} \right)_{\text{episode}}$$

$$= \Sigma \left( \text{weight} \times \text{incipient lethal-environmental DO} \right)_{\text{episode}}$$

Once the weights are calculated, the daily oxygen deficit is calculated. It is a function of the difference between the incipient lethal DO and the measured DO concentrations. This difference must be weighted in proportion to how fast 10% mortality occurs at the measured temperature and DO.

Figures 4, 5, and 6 give three examples of low DO episodes and the associated index values. These examples use Tom Malone's data from his transect of the upper Bay, just below the Choptank River. Observations were made most of the hypoxic season. Bottom waters near the western shore (Station 1, about 9 m deep) and near mid-channel (Station 3, about 25 m deep) had index values several times greater than the "alarm" range. It is safe to say that these areas were hypoxic enough in 1986 to cause greater than 10% oyster mortalities where oysters were present. Where oysters were absent, low oxygen precluded oyster beds even if other conditions were adequate. Oxygen declines at the last, near mid-channel example (Station 4, about 7 m deep) never fell low enough to cause oxygen debt, so the index was zero.

Comparable index values throughout the Bay would indicate how much of the existing and potential oyster beds suffer "warning" and "alarm" levels of hypoxia. Perhaps even more significantly, since governments are already committed to remediating hypoxia in the Bay, the index can help quantify how much remediation is needed to regain acceptable water quality.

As we emphasized, more laboratory measurements of hypoxic-induced mortality in oysters are necessary for reliable index values. These are relatively inexpensive measurements to make. Given more reliable LC10 curves, index values could be calculated for all locations at which we know the seasonal DO calculations, thereby characterizing areas of the Bay that are not affected by hypoxia and those in "warning" and "alarm" ranges of the index.

Further, some other hypoxic effects can be quantified and indexed. One could, at minimal cost, quantify growth reduction and mortality of oyster spat and larvae; and, at greater cost and less accuracy, quantify avoidance by blue crabs and other resource species.

The index makes explicit both specific hypoxic effects and their social importance, factors that are typically assessed in vague and ad hoc ways. We suggest that use of
the index would facilitate decisions about remediating hypoxia in more consistent and defensible ways.

Some will find the index too complicated. It is possible to define a simplified version, but we are reluctant to simplify by relaxing the tight linkage possible between hypoxia and effects. If decisionmakers require a less complicated index, simpler approaches to interpreting Figures 4–6 are evident.

Figure 1. Scale and levels of concern for the index.
Figure 2. Days of exposure to reduced oxygen concentrations, at specified temperature, causing 10% mortality in the American oyster. The obviously uncertain extrapolations are for illustrative purposes only. Each circle represents an LC10 value based upon 20 oysters. (Data courtesy of William B. Stickle, Jr., Louisiana State University.)

Figure 3. Incipient lethal (LC10) curve for the American oyster; the DO and temperature interactions just sufficient, over indefinitely long exposures, to kill 10% of adult oysters.
Figure 5. 1986 Seasonal (DO) and Incipient Lethal (DO) for oysters in upper Chesapeake just below Choptank River (Data courtesy of T.C. Malone, UM)

Figure 4. 1986 Seasonal (DO) and Incipient Lethal (DO) for oysters in upper Chesapeake just below Choptank River (Data courtesy of T.C. Malone, UM)
Figure 6. 1986 Seasonal (DO) and incipient lethal (DO) for oysters, in upper Chesapeake just below Choptank River (Data courtesy of T.C. Malone, University of Maryland).

O'Connor: I am not certain. Kennedy: This index, Joel, is it being used anywhere, as a management tool yet, or... what are the plans for the future?

O'Connor: It is not being used yet - I am shopping around for customers, looking for decision-makers who could help. The Oyster Index would be a good tool if they could resolve. I would like to work with them in actually applying the Index. I feel that there are several areas where it could be applied, especially in New York. The surf clam data is a good index, and it appears that the oyster data, for instance, would be adequate. That is what needs to be done: define the quantitative linkage between the oxygen fields and the effects.
sured practically, with useful precision, over hypoxic areas of the Chesapeake.

Jonas: Along those lines, you have something like the issue of shipping live blue crabs, for example, the ability to survive shipping.

Mackierman: In 1984, a lot of watermen reported that the live crabs seemed weak, a lot didn’t survive shipping or even getting to the dock. This was a bad anoxia year, so the crabs may have been very stressed.

Question: How sensitive is your index to the periodicity of dissolved oxygen measurements?

O’Connor: It assumes that the DO is continuously below that incipient lethal concentration — that if you have something like diurnal or aperiodic infusion of oxygenated water, it just doesn’t apply, because I just don’t know how fast different organisms can repay that oxygen debt. With salmonids, they think it is on the order of 24 hours. And I don’t know many other organisms for which this measurement has really been made.

Comment: So your index would be really most appropriate in the deep basins, but in areas where you have this tilting occurring, in the shallower areas, you have a problem on how often you go out and measure your dissolved oxygen event.

O’Connor: Right, what you could do in a case like that is measure the index over the longest period at which oxygen is continuously below that incipient lethal concentration. And that would be the conservative estimate of the effect over the whole season.

Question: You only need one episode?

O’Connor: Right, but for something like oysters, for all I know it may only take something like 3 hours of oxygenated water and they can repay all of this oxygen debt.
Houde: I guess you are right — there are not many data to do anything with in a retrospective analysis.

Hennemuth: There hasn't been much — in 10 or 12 years of data — it is uneven.

Jonas: Two things relative to that — one is, within these NOAA/Sea Grant DO projects for 1987, Dr. Peter DeFur from George Mason is going to work on the hypoxic influence on molting blue crabs. He believes they are under severe oxygen stress at this time. During the molting period, they are unable to ventilate, and any stress at that period might provide a very sensitive biological measure of the impact. They can't go anywhere, they are waiting and if one of these little oscillations appears to occur — and even in the Patuxent, we have seen DO at the surface in the 3.0 mg/l range, up in the mouth of the Patuxent River — then you might in fact have a severe impact on molting crabs right there. The other thing to note in passing, is that some of Dave Cargo's oxygen work from 1957 after the incident of mortality of blue crabs in crab pots, — I think it is a CBL technical report, I don't think it is out in the open literature anywhere — there is some data for blue crab survival, and that sort of thing, in relation to dissolved oxygen.