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Interactive comment on "Coastal hypoxia responses to remediation" *by* W. M. Kemp et al.

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General Comments: Introductory material in sections 1 through 3 provides detail on why hypoxia is a growing problem in coastal areas and factors that lead to the formation of hypoxia. The material is a bit repetitive, but includes enough information to explain the problems associated with low dissolved oxygen (DO). For trophic effects of hypoxia additional information can be found in Baird et al. (2004).

All the case studies do a good job of pointing to the need to have knowledge of a system's response to the complex problems associated with eutrophication before conclusions can be drawn as to the effectiveness of management actions. The concluding section provides a good summary of the key points made throughout the paper.

Specific Comments: The topology used for describing four different forms of hypoxia follows what other researchers have used, but with some departure. Permanent used to describe hypoxia that is present all year. Persistent seasonal used to describe a broad range of systems that develop hypoxia typically in the warmer seasons from a combination of stratification and enhanced primary production. Episodic used to describe systems that have several separate hypoxic events per year and also those systems that do not have hypoxia every year. Diel used to describe hypoxia that occurs on a daily basis.

Continuous measurement of DO, now possible with the advent of affordable water quality logging equipment, show that high frequency episodic and diel hypoxia are more common then previously thought. Both small and large systems can experience many short-term low DO events in a season (see recent studies by; Verity et al. 2004, Tyler and Targett 2007, Tyler et al. 2009). Diel hypoxia can also occur even in the absence of water column stratification (Verity et al. 2004).

Diel and episodic hypoxia tend to be less lethal to benthic organisms than permanent and persistent seasonal hypoxia. Physiological and behavioral adaptations appear to be sufficient to allow for survival during the nighttime hypoxic period or short duration episodic events. Mobile fishes migrate out and in of these systems as dissolved oxygen declines and rises again, and may take advantage of stressed prey resources (Pihl et al. 1992, Bacheler et al. 2009, Tyler et al. 2009). Part of the benthic response to diel hypoxia mirrors that of seasonal hypoxia with lower diversity and dominance by tolerant species (Tuzzolino 2008). However, these smaller systems appear to be preconditioned to organic enrichment stress, so mortality is not a typical response.

Section 4 deals with theoretical trajectories for hypoxia response to remediation and is based on Scheffer et al. (2001) catastrophic shifts in ecosystems. As pointed out hypoxia is but one of many undesirable problems associated with eutrophication and linking hypoxia to nutrients with catastrophe theory may be more complex than presented. Catastrophe theory provides a topological approach to analysis of dynamic systems that exhibit large, abrupt change in response to stressors (Jones and Walters 1976). An early application was that of Jones and Walters (1976) to fishery development and collapse. Catastrophe theory provided a graphical model to illustrate the relationship between stock size, fleet size, and efficiency of fishery gear. In the approach taken by Scheffer et al. two factors are plotted against each other. One factor is External Condition (nutrient loading) and the other is Ecosystem State (in this case hypoxia intensity). It is important that the external condition not be an interactive part of the system (Schaffer and Carpenter 2003). While Schaffer and Carpenter (2003) point out that the effect of nutrient load on a lake would be a reasonable example of and external condition, given the complex interactions of nutrient load with biological and physical processes in the formation of hypoxia, I do not think catastrophe theory fits well as presented. There are too many interconnected and interacting external condition variables for the ecosystem state relative to hypoxia intensity to be reliably tracked by only nutrient load. The complexity of the situation can be in Figure A were hypoxia is just one many variables responding to nutrients.

In section 5 on the observed hypoxia responses remediation Kemp et al. do a good job linking nutrient load control through management actions to reduction in hypoxia. The best example for this comes from the implementation of the Clean Water Act in 1972 in the US. A decade after the Clean Water Act municipal biological oxygen demand (BOD) decreased by 46% and industrial BOD by 71% (Smith et al. 1987). Smith et al. (1987) analyzed trends in water quality from 1974 to 1981 using 380 stations from all over the US and found control of point sources was biggest factor in improved water quality, mostly from industrial and municipal discharges. Nonpoint pollution from urban and agricultural runoff increased over this period and will prevent achievement of national water quality goals as set out in the Clean Water Act.

Case Studies: The case studies selected to show the complexities between nutrient load and hypoxia do provide good detail but they are variable in detail and terminology used to describe the systems.

Patuxent River: In a small tributary like the Patuxent River the idea that nutrients must be managed from both landward and seaward sources is good. At times there is little

attention give to the interaction of smaller systems with their connections to the sea. This may become a more important connection for systems affected by upwelling as has been recently reported for the Yaquina Estuary, Oregon (Brown et al. 2007).

Black Sea: For the Black Sea, I would disagree with Kemp et al. when they say 'The development, variability, and ultimate removal of the hypoxic zone in the northwester shelf is an example of how the extent of hypoxia can respond to changes in nutrient loads, as mediated by climatic variability and food web shifts resulting from over-fishing.' Mee (2006) presents a very strong case linking the reduction in hypoxic area from 40,000 km2 in 1990 to 0 km2 in 1993 to economic forces and not climate. This response of improved DO over the northwest Black Sea continental shelf was not climatic or food web related.

Baltic Sea: Over the last 15,000 years the Baltic Sea has alternated between being either a freshwater and a brackish marine system. The Baltic's present brackish water condition is about 2,000 year (Karlson et al. 2002) so it does not seem relevant to the current DO conditions in the Baltic to discuss events in the Holocene as an indication that hypoxia was always present. Recent assessments of eutrophication and hypoxia/anoxia in the Baltic all point to greatly deteriorated bottom habitat quality since the 1930s (see Karlson et al. 2002). The Baltic Sea is clearly prone to development of hypoxia but its geological history has little to do with today's DO conditions.

Chesapeake Bay: I would not characterize the shift in volume of hypoxia before and after 1985 as a regime shift. Models developed by Hagy et al. (2004) show an increasing volume of hypoxia but not shift in the mid 1980s. After 1985 there does appear be an increase in the variability of hypoxia from year to year (Figure B). I would argue that by 1985, given the geomorphology and physics of the main stem Chesapeake Bay, the Bay reached it's capacity for holding the given hypoxic water volume and that variation from year to year reflected changes in weather. As pointed out in the concluding section, 'Physical features of the ecosystem appear to set limits on hypoxia extent...' After 1985 the Chesapeake Bay oscillated around a mean of 8.4 (SD= 2.2) x 103 km3 (data from Hagy et al. 2004) with little upward trend in volume (Figure B).

Gulf of Mexico: Continental shelf hypoxia was first reported in the northern Gulf of Mexico associated with the Mississippi/Atchafalaya Rivers in the early 1970s (Rabalais et al. 1999).

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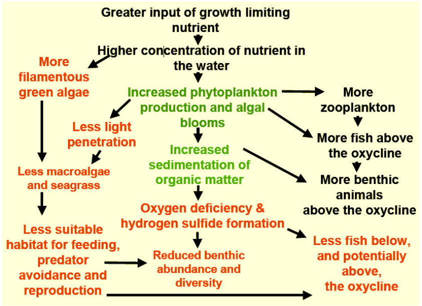

Figure A. Schematic representation of the cascading effects of increasing nutrients is a coastal ecosystem. The harmful effects are in red. Modified from Rabalais et al. 2009.

Fig. 1. Figures for Kemp et al. review