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Invited review article

Retrospective environmental biomonitoring – Mussel Watch expanded

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A B S T R A C T

Monitoring bioavailable contaminants and determining baseline conditions in aquatic environments has become an important aspect of ecology and ecotoxicology. Since the mid-1970s and the initiation of the Mussel Watch program, this has been successfully accomplished with bivalve mollusks. These (mostly) sessile organisms reliably and proportionately record changes of a range of organic and inorganic pollutants occurring in the water, food or sediment. The great majority of studies have measured the concentration of pollutants in soft tissues and, to a much lesser extent, in whole shells or fractions thereof. Both approaches come with several drawbacks. Neither soft tissues nor whole shells can resolve temporal changes of the pollution history, except through the analysis of multiple specimens collected at different times. Soft tissues and shell fractions provide time-averaged data spanning months or years, and whole shells time-averaged data over the entire lifespan of the animal. Even with regular sampling of multiple specimens over long intervals of time, the resulting chronology may not faithfully resolve short-term changes of water quality. Compounding the problem, whole shell averages tend to be non-arithmetic and non-linear, because shell growth rate varies through seasons and lifetime, and different shell layers often vary ultrastructurally and can thus be chemically different from each other. Mussel Watch could greatly benefit from the potential of bivalve shells in providing high-resolution, temporally aligned archives of environmental variability. So far, only circa a dozen studies have demonstrated that the sclerochronological approach – i.e., combined growth pattern and high-resolution chemical analyses – can provide sub-seasonally to annually resolved time-series documenting the history of pollution over centuries and even millennia. On the other hand, the sclerochronological community has failed to fully appreciate that the formation of the shell and its chemical composition is controlled by the soft parts and that a robust interpretation of the shell record requires a detailed understanding of bivalve physiology, behavior and ecology. This review attempts to bring together the Mussel Watch and sclerochronology communities and lay the foundation of a new subdiscipline of the Mussel Watch: retrospective environmental biomonitoring. For this purpose, we provide an overview of seminal work from both fields and outline potential future research directions.

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1. Introduction

Aquatic ecosystems are profoundly affected by anthropogenic disturbances from pollution. Coastal waters and estuaries are particularly vulnerable as they have often been focal points of human settlement and resource use throughout history (Lotze et al., 2006; Marean et al., 2007). The biological effects of pollutants include impaired physiological processes due to the accumulation of substances to toxic levels and transfer of these substances through different trophic levels. Since the mid-1970s, attempts to monitor coastal, fluviatile and lacustrine pollution have been increasingly discussed and have led to the initiation of the "Mussel Watch" program (Goldberg, 1975, 1986; Goldberg et al., 1978), in which bivalve mollusks have been used to monitor a suite of common pollutants mobilized by human activities (Goldberg et al., 1983; Beliaeff et al., 1997; O'Connor, 1998; Apeti et al., 2010; Shiel et al., 2012).

The monitoring of pollutant levels in the environment can be done in a number of ways, depending on the specific focus of a study. Measuring the concentration of inorganic (e.g., heavy metals, radionuclides, rare earth elements) and organic pollutants (dichloro-diphenyl-trichloroethane, DDT; hexachlorocyclohexanes, HCHs; polychlorinated biphenyls, PCBs; polycyclic aromatic hydrocarbons, PAHs etc.) in the environment can be accomplished by direct chemical analysis of water and sediment (e.g., Superville et al., 2014). However, such data provide little information about the concentration of bioavailable toxins, which are those available for uptake and accumulation by living organisms. Bioavailable contaminants are the most relevant portion from an ecotoxicological perspective (Rainbow, 1995; Soto et al., 1995), because they ultimately pose a potential health risk to humans and the food sources that they depend upon. Thus, monitoring levels of bioavailable pollutants was the initial goal of the Mussel Watch initiative (e.g., Goldberg et al., 1978; Steimle et al., 1986; Tavares et al., 1988; Vieweg et al., 2012).

The Mussel Watch was, and is still, a successful biomonitoring strategy because of several advantages in the use of bivalves as sentinels, as opposed to other organisms or even direct measurements of pollutants in the water or sediment (Farrington et al., 1983; Goldberg, 1986). First, soft-parts and shells of bivalves contain records of pollutants that are averaged over some accumulation interval (Fig. 1A + B). Such accumulation intervals are defined by various metabolic processes but do vary among different species, environments and seasons of the year. This is advantageous over direct measurements of pollutants in the environment which would only provide temporal and spatial snapshots unless expensive instrumental networks were installed to monitor pollutants continuously over long periods of time and at various different localities. A second advantage that bivalves offer is their sedentary lifestyle, which enables them to record an environmental signal from only one locality, rather than a spatial average that would be produced by a mobile organism. Bivalves also have the ability to bioaccumulate pollutants in their tissues to many times the concentration in the ambient environment, which facilitates chemical analyses. Finally, bivalves have a very broad biogeographic distribution and can be very abundant in many environments, creating the opportunity for the analysis of numerous specimens in just about any aquatic setting.

The great majority of studies conducted under the umbrella of the Mussel Watch program have analyzed the concentration of pollutants in soft tissues (Fig. 1A) and, to a much lesser extent, in whole shells or fractions thereof (Fig. 1B) (Purchase and Fergusson, 1986; Nicholson and Szefer, 2003; Bellotto and Miekeley, 2000, 2007; Shiel et al., 2012). However, analyses of both soft tissues and whole shells do come with several drawbacks. Most importantly, neither method can resolve temporal changes of the pollution history, except through the analysis of multiple specimens collected at different times. Even then, any single specimen can only provide time-averaged data over several months or years (soft parts; fractions of shells) or the entire lifespan of an individual (whole shell). Even with regular sampling of multiple specimens over long periods of time, the resulting time-series may not faithfully resolve short-term changes of water quality on seasonal to inter-annual time-scales. Moreover, pollution records assembled from multiple specimens living at different times may be subject to a high degree of statistical noise resulting from slight differences in the environment of collection and differences in the elemental content among specimens determined by individual genotype/physiology (e.g., Carriker et al., 1982). Because of these limitations, new study sites will only yield informative time-series after years of monitoring.

Another limitation of monitoring strategies based on soft tissues is the relative youth of this type of research in general. Mussel Watch studies typically cannot yield information on pollution levels in the distant past, as pre-1970 data are scarce (Cantillo, 1998). One noteworthy exception is a study which used canned blue mussels to study coastal contamination by DDT, HCHs, PCBs, PAHs during the 1940s (Apeti et al., 2010). That study notwithstanding, biomonitoring studies based on soft tissues are severely limited when it comes to long-term changes in environmental pollution levels. The documentation of anthropogenically-induced changes to organisms and ecosystems during the last 40 years (i.e., since initiation of the Mussel Watch) is an important task, yet a thorough understanding of pollution and natural variability in ecosystems requires much longer time-series. In order to more accurately assess the current health of ecosystems, it is necessary to develop a detailed understanding of the magnitude of anthropogenic change in reference to a baseline estimate of environmental parameters prior to human modification. Only with such an approach can the magnitude of current and ongoing change be understood. The ultimate goal of such research should be the establishment of realistic and attainable goals for conservation and remediation of ecosystems most critically threatened by anthropogenic change. Centuries of exploitation and anthropogenic modification of aquatic ecosystems have obscured the magnitude of the change that such ecosystems endured, because historical observations – often limited to the last 100 years – cannot capture the pristine state. This uncertainty about the natural state of aquatic ecosystems is one of the most profound questions facing biological and environmental conservation efforts (Jackson et al., 2001; Willis and Birks, 2006; Knowlton and Jackson, 2008). References to baseline conditions that show no discernible human influence and a knowledge