Ecological Indicators 82 (2017) 539–550

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Diatom teratologies as biomarkers of contamination: Are all deformities ecologically meaningful?

Isabelle Lavoie[a,*], Paul B. Hamilton[b], Soizic Morin[c], Sandra Kim Tiam[a,d], Maria Kahlert[e], Sara Gonçalves[e,f], Elisa Falasco[g], Claude Fortin[a], Brigitte Gontero[h], David Heudre[i], Mila Kojadinovic-Sirinelli[h], Kalina Manoylov[j], Lalit K. Pandey[k], Jonathan C. Taylor[l,m]

[a] Institut National de la Recherche Scientifique, Centre Eau Terre Environnement, 490 rue de la Couronne, G1K 9A9, Québec (QC), Canada
[b] Phycology Section, Collections and Research, Canadian Museum of Nature, P.O. Box 3443, Station D, Ottawa, K1P 6P4 Ontario, Canada
[c] Irstea, UR EABX, 50 Avenue de Verdun, 33612 Cestas Cedex, France
[d] Molécules de communication et adaptation des microorganismes, Cyanobactéries, Cyanotoxines et Environnement, Muséum National d'Histoire Naturelle, 12 rue Buffon, F-75231 Paris, Cedex 05, France
[e] Swedish University of Agricultural Sciences, Department of Aquatic Sciences and Assessment, P.O. Box 7050, SE- 750 07 Uppsala, Sweden
[f] Departamento de Biologia, Universidade de Aveiro. Campus de Santiago, 3810-193 Aveiro, Portugal
[g] Department of Life Sciences and Systems Biology, University of Turin, via Accademia Albertina 13, 10123 Turin, Italy
[h] Aix Marseille Univ, CNRS, BIP, UMR 7281, IMM, 31 Chemin J. Aiguier, 13 402 Marseille Cedex 20, France
[i] DREAL Grand Est/Service Eau, Biodiversité et Paysage/Laboratoire d'hydrobiologie, 14 Rue du Bataillon de Marche n°24, 67200 Strasbourg, France
[j] Department of Biological and Environmental Sciences, Georgia College and State University, Milledgeville, GA, 31061, USA
[k] Institute of Green Environmental Research, Incheon National University, 119, Academy-ro, Yeonsu-gu, 22012 Incheon, Republic of Korea
[l] Unit for Environmental Sciences and Management, North-West University, P Bag X6001, 2520 Potchefstroom, South Africa
[m] South African Institute for Aquatic Biodiversity (SAIAB), P Bag 1015, 6140 Grahamstown, South Africa

ARTICLE INFO

Keywords:
Bioassessment
Biomarker
Contaminants
Deformities
Diatoms
Teratologies

ABSTRACT

Contaminant-related stress on aquatic biota is difficult to assess when lethal impacts are not observed. Diatoms, by displaying deformities (teratologies) in their valves, have the potential to reflect sub-lethal responses to environmental stressors such as metals and organic compounds. For this reason, there is great interest in using diatom morphological aberrations in biomonitoring. However, the detection and mostly the quantification of teratologies is still a challenge; not all studies have succeeded in showing a relationship between the proportion of abnormal valves and contamination level along a gradient of exposure. This limitation in part reflects the loss of ecological information from diatom teratologies during analyses when all deformities are considered. The type of deformity, the severity of aberration, species proneness to deformity formation, and propagation of deformities throughout the population are key components and constraints in quantifying teratologies. Before a metric based on diatom deformities can be used as an indicator of contamination, it is important to better understand the "ecological signal" provided by this biomarker. Using the overall abundance of teratologies has proved to be an excellent tool for identifying contaminated and non-contaminated environments (presence/absence), but refining this biomonitoring approach may bring additional insights allowing for a better assessment of contamination level along a gradient. The dilemma: are all teratologies significant, equal and/or meaningful in assessing changing levels of contamination? This viewpoint article examines numerous interrogatives relative to the use of diatom teratologies in water quality monitoring, provides selected examples of differential responses to contamination, and proposes solutions that may refine our understanding and quantification of the stress. This paper highlights the logistical problems associated with accurately evaluating and interpreting teratologies and stimulates more discussion and research on the subject to enhance the sensitivity of this metric in bioassessments.

1. Introduction

Diatoms are useful tools in the bioassessment of freshwater ecosystem integrity and are presently included in numerous water quality monitoring programs worldwide. A variety of diatom-based indices have been developed using different approaches (e.g., Lavoie et al., 2006, 2014 and references therein; Smol and Stoermer, 2010 and references therein). Most indices were created to assess ecosystem health

* Corresponding author.
E-mail address: ilavoie.bio@gmail.com (I. Lavoie).

http://dx.doi.org/10.1016/j.ecolind.2017.06.048
Received 19 January 2017; Received in revised form 21 June 2017; Accepted 22 June 2017
Available online 26 July 2017

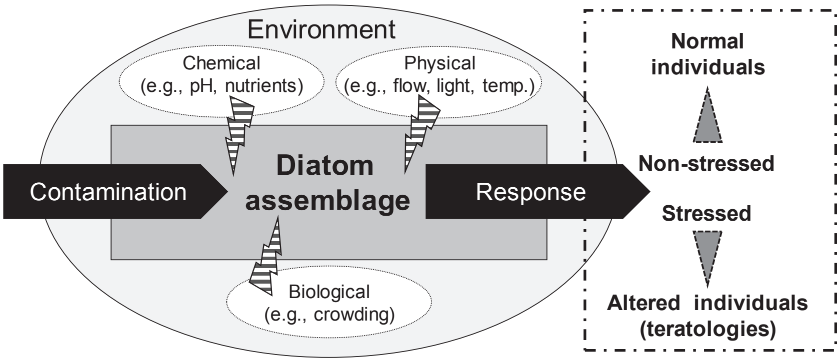

Fig. 1. Conceptual model representing the response of a diatom assemblage to environmental and anthropogenic perturbations.

reflecting general water quality and regional climate. There are also countless studies reporting the response of diatom assemblages to metal contamination (see review in Morin et al., 2012) and to organic contaminants (Debenest et al., 2010). However, diatom-based indices have not been developed to directly assess toxic contaminants (e.g., metals, pesticides, hydrocarbons). Contaminant-related stress on biota is difficult to assess when lethal impacts are not observed. Diatoms, by displaying aberrations in their valves (deviation from normal shape or ornamentation), have the potential to reflect sub-lethal responses to environmental stressors including contaminants. Observed deformities can affect the general shape of the valve, the sternum/raphe, the striation pattern, and other structures, or can be a combination of various alterations (Falasco et al., 2009a). Other stressors such as excess light, nutrient depletion, and low pH also have the potential to induce frustule deformities (Fig. 1; see review in Falasco et al., 2009a). However, the presence of abnormal frustules (also called teratologies or deformities) in highly contaminated environments is generally a response to toxic chemicals. For this reason, there is great interest in using morphological aberrations in biomonitoring. Teratologies may be a valuable tool to assess ecosystem health and it can be assumed that their frequency and severity are related to magnitude of the stress. We focussed our main discussion on teratologies as biomarkers although other descriptors such as valve densities, species diversity and assemblage structure are also commonly used to evaluate the response of diatom assemblages to contaminants.

Based on the current literature, the presence of deformities in contaminated environments is considered an indication of stress; however, detection and quantification of teratologies is still a challenge. In other words, not all studies have succeeded in showing a relationship between the proportion of abnormal valves and contamination level along a gradient of exposure (see Sections 3.2 and 5.1 for examples). Before a metric based on diatom teratologies can be used as an indicator of contamination, we believe it is imperative to better understand the "ecological information" provided by the different types of deformities and their severity. Furthermore, how are teratologies passed through generations of cell division? These aspects may influence our assessment and interpretation of water quality.

This paper will not provide a detailed review of the abundant literature on the subject of diatom valve morphogenesis or the different types of teratologies and their causes, but will examine numerous interrogatives relative to the use of diatom teratologies for the assessment of various types of contamination. This work is an extension of the discussion issued from the collaborative poster entitled "*Diatom teratologies in bioassessment and the need for understanding their significance: are all deformities equal?*" presented at the 24th International Diatom Symposium held in Quebec City (August 2016). The participants were invited to take part in the project by adding comments, questions and information directly on the poster board, and by collaborating on the writing of the present paper. Numerous questions were presented (Table 1) related to the indicator potential of different types of deformities and their severity, the transmission of teratologies as cells divide, and species proneness to deformities. These questions, we believe, are of interest when using diatom teratologies as biomarkers of stress. This topic is especially of concern because diatom teratologies are increasingly used in biomonitoring as shown by the rising number of publications on diatom malformations (Fig. 2). With this paper, we aim to initiate a discussion on the subject. Hopefully, this discussion will create new avenues for using teratologies as biomarkers of stress and contamination. The ultimate goal would be the creation of an index including additional biological descriptors to complement the teratology-based metric.

Table 1
List of questions that initiated this communication as well as questions raised by participants during the 24th International Diatom Symposium (IDS 2016, Quebec City).

Teratology formation and transmission
• How are deformities transmitted to the subsequent generations?
• The newly-formed valve is an exact copy (or smaller) of the mother cell; in this case, how does the first deformity of the valve outline appear?
• Are abnormal ornamentation patterns observed on both valves?
• Are deformed cells able to survive and reproduce?
Ecological meaning
• Are deformities equal between different species? Are all types of deformities equal within the same species?
• Are all toxicants likely to induce similar deformities? (or are deformities toxicant-specific?)
• Should a deformity observed on a "tolerant" species (versus a "sensitive" species) have more weight as an indicator of stress?
Issues with teratology assessment
• Certain types of deformities are difficult or impossible to see under a light microscope, particularly for small species. Should problematic taxa be included in bioassessments based on teratologies?
• How to assess deformities on specimen that are in girdle view?
• How should the "severity" of a teratology be assessed?
Implications for biomonitoring
• The sternum is the initial structure to be formed; should an abnormal sternum (including the raphe) be considered more important/significant than other types of aberrations?
• Proneness to produce abnormal valves and sensitivity to specific contaminants are key factors for the inclusion of teratological forms in diatom indices. How to quantify them?
• What is the significance of deformities in a single species versus multiple species in an assemblage?

2. Teratology formation and transmission

2.1. Valve formation

Current routine identifications of diatom species are based on morphological characters such as symmetry, shape, stria density, and ornamentation. The characteristic shape of each diatom species results from a combination of genetic and cellular based processes that are regulated by environmental factors. There is a wealth of literature on valve morphogenesis, based both on ultrastructure observations and cellular (molecular and biochemical) processes. Descriptions of the processes involved in valve formation are provided, among others, by