

Application Of Foraminifers In Ecotoxicology: Retrospect, Perspect And Prospect

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Abstract:

In view of the extensive use of foraminifers for the pollution monitoring especially their unmatched utility in deciphering the temporal variation in the type and concentration of pollutants at a given location, the literature dealing with the application of foraminifers for pollution studies has been reviewed. The pollution monitoring through foraminifers started with attribution of peculiar foraminiferal features at any location to the circumstantial presence of pollutants at that site. These peculiar features of the foraminifers in polluted areas included, variation in the abundance of total, calcareous and agglutinated foraminifers, species diversity, abnormal tests, etc. The abnormalities of tests included stunted growth, abraded margins, dissolved ornamentations, etc. Initially, much attention was paid to the effects of sewage pollution on the foraminifers but later on all kinds of human induced as well as natural pollutants came under the preview of foraminiferologists working on pollution aspects. The advantage of application of foraminifers, over other chemical and biological techniques, for pollution monitoring lies in their potentiality to decipher temporal variation in type and concentration of pollutants at any site even in the absence of pre-pollution studies, based on the recovery of foraminifers from the sediment core samples. Realizing the potential application of characteristic foraminiferal features from the polluted areas to decipher the variation in introduction and concentration of pollutants at any given location with time, efforts were made to characterize the specific types of foraminiferal features to the specific pollutants. It was at this point that the need of culture studies was widely felt which resulted in numerous lab and field culture studies where foraminifers were subjected to specific pollutants in order to document their response to these pollutants and to develop effective foraminiferal proxies for pollution monitoring through time. Such studies are still going on and it is felt that culture studies need to be supplemented with advanced crystallographic and molecular studies in order to find the mechanism through which foraminifers respond to the pollutants.

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INTRODUCTION

Foraminifers, almost exclusively marine, unicellular protists, generally consisting of a hard covering of calcium carbonate called test, have extensively been used for studies related to paleoclimatic reconstruction, sediment transport, archaeology, etc. The utility of foraminifers for such studies arises from their high-sensitivity to minute variations in the physico-chemical characteristics of the ambient environment. The response of foraminifers to the changed environmental conditions is reflected in the variation in abundance and morphology of the test. The test of foraminifers has high preservation potential thus making these microorganisms one of the most useful proxy for the long as well as short-term temporal variation in the amount and type of toxins in all kinds of marine environments, especially the near-shore coastal areas.

As per U.S. Environmental Protection Agency, pollution is defined as, “Generally, the presence of a substance in the environment that because of its chemical composition or quantity prevents the functioning of natural processes and produces undesirable environmental and health effects”. Thus pollution affects all aspects of life on earth and the incorporation of these effects of pollutants by some of the life forms like foraminifers makes them effective indicator for pollution. The application of foraminifers for pollution monitoring is based on the variation in population (Total Foraminiferal Number, TFN), species diversity (TSN) and abnormalities of the foraminiferal tests in the areas affected by pollution. In almost all the studies, dealing with this aspect of foraminifers, the variation in abundance of species and abnormalities in foraminiferal tests was attributed to the pollutants based on circumstantial evidences. This characteristic of foraminifers to incorporate the signatures of presence of pollutants and preserve them was proposed to be effective tool for temporal pollution monitoring studies. But one of the drawbacks of this work that hampered the effective application of foraminifers for pollution monitoring was the lack of availability of studies documenting presence of specific foraminiferal features from areas affected by specific pollutants and also the presence of similar foraminiferal characteristics from few naturally stressed areas (See Boltovskoy et al. 1991, for review). Therefore, the quest for more and more characteristic foraminiferal features, from polluted environments, continued with rigorous field based studies.

Considering the huge amount of work carried out to characterize effects of pollution on foraminifers, time and again efforts have been made to compile the available literature

(Boltovskoy and Wright 1976; Boltovskoy et al. 1991; Yanko et al. 1994; Alve 1995; Yanko et al. 1999; Scott et al. 2001) for the benefit of the workers venturing in the field of application of foraminifers for pollution monitoring. In the present study, the gradual advancement of the application of foraminifers for the pollution monitoring has been dealt along with a note on the future course of such studies.

Advantage of application of foraminiferal characteristics in ecotoxicology

Though it is easier to assess the present state of type and concentration of pollutants at any given location by chemical and biological techniques, both of these techniques have limitations in assessing the variation in type and concentration of pollutants at a given location during pre-pollution period when similar studies were not carried out. Also, if the discharge of the pollutants has been stopped temporarily, then there are chances of getting anomalous results about the presence of pollutants, as with time the concentration of the pollutants in the water column will get diluted to significantly lower than actual concentrations. Foraminifers have an edge over the rest of the pollution monitoring techniques in such studies as the adverse effects of pollution are incorporated into the tests, which have excellent preservation potential thus providing concrete evidence for the presence and duration of existence of pollutants in the affected area.

These advantages lead to the gradual progress of application of foraminifers for pollution studies, which is also reflected in the trend in the number of papers dealing with the pollution aspects of foraminifers published in various journals. Detailed survey of literature (survey includes results from Aquatic Sciences and Fisheries Abstracts, Scencedirect.com along with some of the peer-reviewed journals that publish results of foraminiferal studies) since the year 1976 onwards reveals an increase in the number of studies involving application of foraminifers for pollution studies (Fig.1). The results indicate that till late eighties little attention was paid to this aspect of foraminifers. But early nineties reported a phenomenal rise in the number of studies involving application of foraminifers for pollution monitoring. The similar trend continued in the late nineties and further in this century also. But an insight into the survey results indicate that not many studies are reported in the journals devoted to the environmental pollution especially marine pollution studies, e.g. only three papers were published in the journal, “Marine Environmental Research” till the year 2003, while in case of “Marine Pollution

Bulletin” a journal entirely devoted to the pollution studies from the marine areas, this number was a meager four. It is found that most of the results were published in “Journal of Foraminiferal Research” or in local journals/conference proceedings. Therefore, it is suggested that more and more results be published in widely-circulated journals dealing with environmental/pollution aspects.

Early stage: Foraminiferal characteristics from sewage polluted areas

The first published record of effect of pollution on foraminifers was that of Zalesny (1959) who noted that the foraminiferal characteristics were altered in the region affected by Hyperion sewage outfall as compared to the adjacent unaffected areas. He noted that the foraminiferal population in general, increased near the outfall because of increased abundance of few species, which he assigned to the increased availability of nutrients in the sewage outfall. The detailed ecotoxicological application of foraminifers was started by Resig (1960) who while working on the foraminifers of the continental shelf of southern California made extensive observations regarding the effect of various sewage outfalls on the foraminiferal population in the coastal areas. Watkins (1961) observed that the number of both living and dead foraminifers per gram dry sediment increased two to three times the normal number, in the vicinity of the sewage outfall. He further observed that the response of the foraminifers to pollutants varied as per the composition of the test, with arenaceous species being more abundant near the outfall.

In all of the ensuing studies (Bandy et al. 1964a; 1964b; 1965a; 1965b), effects of pollutants on the foraminifers were observed in terms of relative abundance of total foraminiferal population, living/dead population, species diversity, variation in abundance of a few species and morphological features of the tests. In the beginning, much attention was paid to the variation in the relative population of living and dead foraminifers in the areas affected by pollutants. In general, it was observed that there occurs a dead zone immediately under the outfall marked by the presence of mostly dead and few rare specimens (Bandy 1964b). A short distance away from this dead zone was an area with higher than normal abundance of foraminifers (Schafer 1973). The species diversity was reported to be drastically low in the immediate vicinity of the outfall, since only a few species were able to survive in the adverse environment near the outfall. The number of these species, or so-called opportunistic species, was many fold higher in the polluted areas than the adjacent unaffected areas. Bandy et al. (1964b) noted *Buliminella elegantissima*,

Bulimina marginata denudata, etc., to be abundant in areas affected by pollutant while *Nonionella* group of species was adversely affected by the pollutants. *Eggrella advena*, *Elphidium incertum*, *E. clavatum* group of species was noticed to be able to compete successfully and to reproduce in polluted environments (Schafer et al. 1975). Test wall composition was the deciding factor for variation in the population of foraminifers. Agglutinated species dominated the dead population in the outfall region while calcareous foraminifers were abundant in the live population in dead zone (Bandy et al. 1965b; Nagy and Alve 1987). The spatial extent of the dead zone was determined by the amount of sewage discharged (Bandy et al. 1965b). The observations regarding the impact of sewage discharge are numerous (Table 1).

These studies were followed by work aimed at deciphering the relative tolerance of different organisms to pollution and the response of foraminifers to other sources of pollution.

Effects of industrial pollutants and other anthropogenic activities

Though initially most of the studies concentrated on the effect of sewage pollution on the foraminifers but later the industrial effluents also came under the purview (Table 1). Setty (1976) observed that the deleterious effects of effluents from the fertilizer industry resulted in decreased abundance and increase in diversity of foraminifers. Rao and Rao (1979) reported solution effects and decreased species diversity as a result of effluents from metal industry, while Schafer (1982), Nagy and Alve (1987), Schafer et al. (1991), etc., reported the effects of pollutants emanating from pulp and paper mills. Setty and Nigam (1984) described the effect of acidic and alkaline effluents from fertilizer and metal processing industries while Bhalla and Nigam (1986) noted decline in foraminiferal species diversity and increase in abundance of deformed tests in response to the discharge of ammonia and arsenic from the fertilizer industries. Sharifi et al. (1991) concluded that the presence of heavy metals (Cu, Zn) caused abnormalities in the foraminifers and that deformed tests contained higher concentration of heavy metals than non-deformed specimens. Geslin et al. (1998) reported that presence of trace elements could lead to crystalline disorganizations. In a study aimed at deciphering the effect of heavy metals, Samir (2000) observed that benthic foraminifers are more sensitive to industrial waste containing heavy metals and also less tolerant to pollution as compared to ostracodes and molluscs. Cearreta et al. (2002) and Chatelet et al. (2004) also reported the adverse effects of metallic pollution on the foraminiferal population and species diversity. Yanko and Flexer (1992) suggested a new

method of natural oil-gas trap reconnaissance based on modification of foraminiferal assemblages in the vicinity of gas-seepage points. The same indicator can also be used for monitoring anthropogenic oil and gas slicks. Yanko et al. (1994) described the effects of coal and fuel ash on the benthic foraminiferal community. Attention has also been paid to the adverse effects of aquaculture operations on the benthic foraminiferal community (Grant et al. 1995; Schafer et al. 1995; Scott et al. 1995; Angell et al. 2000) but the results have been conflicting with Schafer et al. (1995) reporting a severe adverse effect while Scott et al. (1995) and Angell et al. (2000) suggested little impact of aquaculture operations on the benthic foraminiferal community. Similar conflicting response has also been reported in case of pollution by hydrocarbons; Mayer (1980) reported ill effect of oil spill on the benthic foraminiferal population and diversity while Vénec-Peyré (1984) observed no effect of presence of hydrocarbons on the relative abundance and species diversity except morphological abnormalities.

Since response of foraminifers from areas affected by almost all possible pollutants was being documented collectively, therefore the need to find the variation in response of foraminifers as per the type of pollutants was widely felt. In order to delineate the specific response of foraminifers to specific pollutants, few attempts were made to supplement the foraminiferal features with geochemical characteristics of the affected area. The physical parameters like salinity and temperature in the affected area were noted and reported along with the foraminiferal characteristics since the beginning of such studies (Watkins 1961; Bandy et al. 1964b). In most of the cases, the supporting geochemical data was taken from the earlier published reports from the same region (e.g. Schafer et al. 1975). Bates and Spencer (1979) reported the results of Adenosine Tri-Phosphate and chlorophyll analysis. The geo-chemical analysis to draw specific conclusions from the foraminiferal features resulted in studies mentioning the effects of trace and heavy metals, emanating from various anthropogenic sources, on the foraminifers (Ellison et al. 1986). Banerji (1992) prepared a detailed report correlating the variation in amount of heavy metals and foraminiferal characteristics. He concluded that while higher concentrations of Fe-Mn-Zn resulted in higher foraminiferal diversity, the increased concentration of Co-Ni-Pb adversely affected the foraminiferal diversity. He listed the foraminiferal genera as per their increasing vulnerability to heavy metals wherein Lagenids had least impact while *Elphidium* group of species were most severely affected.

Deformed tests as indicators of polluted environments

Deformities in the tests of foraminifers from the polluted environments have been one of the important aspects of pollution monitoring studies utilizing foraminiferal characteristics. Abnormalities in tests of certain species were noticed and based on their relative abundance in polluted areas as compared to unaffected areas, were assigned to presence of pollutants, e.g. Watkins (1961) reported more number of *Elphidium spinatum* and *Nonionella basispinata* specimens with additional abnormal spines near the outfall. Similarly while summarizing the effects of pollution on the foraminifers along the west coast of India, Setty and Nigam (1984) reported that the abnormalities included lower than normal ornamentation, deepening of grooves and sutural thickening, enlargement of pores, widening of apertures, erosion along peripheries and induced growth in last few chambers. Yanko et al. (1994) observed stunted tests, additional chambers, invariably larger or smaller chambers and disorientation of the plane of few chambers from the rest, while carrying out foraminiferal study at contaminated sites along the Mediterranean coast of Israel and further by comparing their findings with that of Alve (1991) concluded that abnormalities in the foraminiferal tests in polluted areas are present in both cold as well warm water environments. Increased abundance of abnormal specimens from polluted areas has also been reported by, Bhalla and Nigam (1986), Sharifi et al. (1991), Jayaraju and Reddy (1996), Geslin et al. (1998), Yanko et al. (1998), Samir (2000), Samir and El-din (2001), Elberling et al. (2003), etc. Despite a number of studies mentioning increased deformities in tests from polluted environments this characteristic has not attained the status of an effective parameter since similar features were also observed from the areas subjected to natural ecological stress (Boltovskoy et al., 1991; Debenay et al. 2001). Considering these conflicting reports, researchers have suggested that application of abnormalities to monitor pollution be attempted with care (Geslin et al. 2002). Keeping these difficulties in mind Stouff et al. (1999) tried to understand the cause of different types of abnormalities in *Ammonia tepida* and *A. beccarii*, by subjecting them to different environments under laboratory culture experiments. They recommended the use of different terms for the abnormalities arising during different stages of the life cycle of the foraminifers, viz. ‘deformations’ for the abnormalities incorporated during the life of foraminifers, while the term ‘malformations’ for the abnormalities resulting from unusual ontogenetic development. But still type and amount of abnormalities in foraminiferal tests from polluted areas is a hotly debated topic and extensive culture and field

studies are required in order to arrive at any conclusion regarding the specific abnormalities in response to specific pollutants.

Application in temporal variation of pollutants

The main advantage of application of foraminifers for pollution monitoring, which is a limitation of almost all other techniques, is to decipher temporal variation of pollution levels and has extensively been used at certain places (Table 2). The application of foraminifers for temporal variation of pollutants can be attempted either by collecting core samples in order to get comparative foraminiferal characteristics during pre- and/or post pollution period or by time series surface sediment sampling, i.e. by analyzing the surface sediment samples collected over a period of time spanning the period before the pollutants were introduced into the environment and the period after the introduction of pollutants. Based on such sampling techniques, Schafer (1982) reported that the cessation of dumping activity resulted in recolonization of the previous dumpsites by several benthic foraminiferal species especially *Eggerella advena* and *Ammotium cassis* within a short span of few months with a remarkable increase in both species diversity as well as total foraminiferal population. Nagy and Alve (1987) noted higher abundance of arenaceous foraminifers, while decrease in the relative abundance of calcareous foraminifers in a core in response to the pollution (effluents from paper mill) from the anthropogenic activities. Schafer et al. (1991) while reporting the variation in foraminiferal characteristics of gravity cores collected from Saguenay Fiord, Quebec, Canada, noted that the presence of only allochthonous thecamoebian and reworked planktonic foraminiferal tests in many foraminifera barren core intervals was because of pollution stress. They further noted that the relative abundance of *Cassidulina reniforme*, a calcareous species increased three times as a result of return of favourable conditions that included decrease in the amount of pollutants discharged, as a result of government imposed regulations on the industries.

Grant et al. (1995) based on the cores collected from the areas adjacent to shellfish aquaculture sites showed that the introduction of mussel feces and pseudofeces does not result in any evident change in the foraminiferal population. In the same study it was also observed that the construction of a causeway in the year 1968 and ensuing temperature changes resulted in temporal variation in foraminiferal species composition in the cove by shifting toward calcareous species. Scott et al. (1995) concluded that finfish operation has little environmental impact on

benthic community as suggested from the foraminifera and further that the foraminiferal assemblages in cores provide the only means of obtaining "a priori" information on benthic habitats in the aquaculture operations environments. Cockey et al. (1996) reported a shift in dominance from long-lived, algal-symbiont-bearing taxa in 1959-1961 to small, fast-growing, heterotrophic taxa in 1992 in response to gradually increasing nutrient flux from effluents into south Florida's coastal waters.

Scott et al. (1995), based on a benthic foraminiferal census conducted over a period of thirty years showed that following significant decline in the volume of contaminants, including DDT and solid waste, the benthic foraminifera re-inhabited the region around the outfall, in numbers similar to those found in other non-affected parts of the Southern California shelf and concluded that sensitivity of *Nonionella* spp, should provide good indication of conditions around other environmentally sensitive regions along the California coast. Karlsen et al. (2000) applied the variation in the relative abundance of deformed tests of *Ammonia parkinsoniana* from the Chesapeake Bay as bio-indicator to estimate the timing and degree of changes in dissolved oxygen (DO) resulting from high freshwater flow and increase in nutrient concentrations from the watershed over a period of time. Thomas et al. (2000) also drew similar conclusions based on the time interval study from Long Island Sound. Leduc et al. (2002) concluded that the decrease in the abundance of *Spiroplectammina biformis* relative to *Adercotryma glomerata* could be related to reduction in the industrial waste. Nigam et al. (2002) while comparing the foraminiferal characteristics of the surface samples collected from the Mandovi estuary, with those of Rao (1974) from the same area showed that the increase in the mining waste over a gap of 18 years resulted in drastic decrease in total foraminiferal number and total species number. Ruiz et al. (2004) based on the analysis of 17 cores collected in the Odiel Estuary (SW Spain) concluded that ostracoda and foraminifera could be used as short-term tracers of environmental changes in polluted areas.

In all of these studies the variation in foraminiferal characteristics (population, species diversity, deformities, etc.) were assigned to pollutants based on circumstantial presence of certain pollutants in the affected areas. But for effective application of foraminifers for pollution monitoring studies it was necessary that these characteristic foraminiferal features be differentiated as per the type and concentration of pollutants. The solution for this came with the foraminiferal culture studies.

Culture studies: Experimental proof to field based pollution studies

Delineation of areas affected by pollution from those with natural stress was based on the assumption that natural stress conditions are gradual enough to provide sufficient time to the fauna to either migrate to preferential environment, leaving the space for more adaptive species to thrive, or to adapt to the changed physico-chemical conditions. But pollution is largely an abrupt anthropogenic and recent phenomena that causes a comparatively fast change in physico-chemical conditions, thus providing no opportunity for the fauna to migrate, resulting in perceptible variation in foraminiferal characteristics. Therefore, the need of studies through which the foraminiferal characteristics can specifically be attributed to specific factors (salinity, temperature, heavy metals, organic pollutants, etc.) was widely felt. This led to foraminiferal culture studies wherein foraminifers were subjected to specific pollutants and thus the specific response of foraminifers to that pollutant was documented (Table 3). In the same way the types of abnormalities arising because of extreme ecological conditions can also be documented. As far back as 1976, LeFurgey and Jean conducted an experimental study wherein they observed the response of foraminifers to effluents by maintaining them in effluent affected and control ponds. They concluded that species diversity was approximately 20 percent higher and average number of living foraminifera was approximately 5 times greater in control ponds than in the effluent ponds, thus providing an experimental proof for the field studies. Bresler and Yanko (1995), investigated the interactions of living benthic epiphytic foraminifera with unidentified natural organic compounds (UNOC) derived from decomposed seaweeds, heavy metal ions and three tracer xenobiotics, acridine orange, neutral red and fluorecein, and concluded that the state of the defense system against xenobiotics in benthic epiphytic foraminifera can serve as a very sensitive biomarker for monitoring and prediction of ecological consequences of anthropogenic pollution. Moodley et al. (1998) in order to decipher the specific effect of hydrogen sulfide, byproduct of organic matter degradation and natural gas seepage, on the distribution of foraminifers, subjected the foraminiferal community to induced hydrogen sulfide and concluded that tolerance of sulphidic conditions was restricted to survival and that sulphide may be a prominent distributional factor for benthic foraminifera. Stouff et al. (1999) tried to understand the cause of different types of abnormalities in *Ammonia tepida* and *A. beccarii*, by subjecting them to different environments under laboratory culture experiments. Alve and Olsgard (1999) concluded that the colonization ability of benthic foraminifers is not much affected by the

enrichment of copper in the vicinity. Similarly Gustafson et al. (2000) based on laboratory culture experiments reported that the excess (2.00 nmol/g dry sediment) presence of Tri-*n* Butyltin in the ambient environment of the benthic foraminifers decreases the abundance. Ward et al. (2003) investigated the consumption of food material by foraminifers and found that *Haynesina germanica* did not consume secondary treated sewage-derived particulate organic matter. Cadre et al. (2003) while observing the effects of low pH on *Ammonia beccarii* noted that at lower pH the tests starts dissolving. But laboratory culture studies to observe the response of foraminifers to pollutants are still in there infancy. In India, a beginning has been made in this direction, with establishment of foraminiferal culture studies at National Institute of Oceanography. In one such study live specimens of near-shore benthic foraminiferal species *Rosalina leei* were subjected to different concentration of mercury, and it was noticed that the growth rate as well as the maximum size attained decreased considerably in the specimens subjected to gradually higher concentration of inorganic form of mercury (HgCl₂ dissolved in seawater) (Saraswat et al., 2004). In the same experiment it was also noticed that the specimens subjected to higher concentration of mercury developed abnormalities in the tests including comparatively larger and irregularly oriented outer chambers.

In spite of above-mentioned reports, application of foraminifers for pollution monitoring still needs considerable attention along with more and more field-based studies as evident from the survey of the literature.

Future Strategies

Further laboratory culture studies are needed to decipher the specific response of foraminifers to specific factors. In laboratory culture studies, much emphasis needs to be given to the monospecific culture than to bulk culture, as it will help in identifying the threshold limits of individual species, which can be used for effective monitoring of pollution. The laboratory culture studies needs to be supplemented by advanced crystallographic and molecular studies in order to understand the causes of abnormalities in the tests that may arise either because of incorporation of elements in the crystal lattice of the calcium-carbonate that constitutes the test of foraminifers and thus leading to the abnormalities in the tests, or because of malfunctioning of certain organelles of the single cell that constitute the soft part of the foraminifers. The advanced molecular analysis techniques should extensively be applied in order to find out the variation

incurring into the various protoplasmic components (proteins, lipids, enzymes, fatty acids etc.) due to the presence of xenobiotics. The knowledge thus gained will help in effective application of foraminifers for pollution monitoring.

Further, in order to get better understanding of adverse effects of various anthropogenic activities, foraminiferal analysis be made mandatory during all pre- and post- factory environmental impact assessment surveys.

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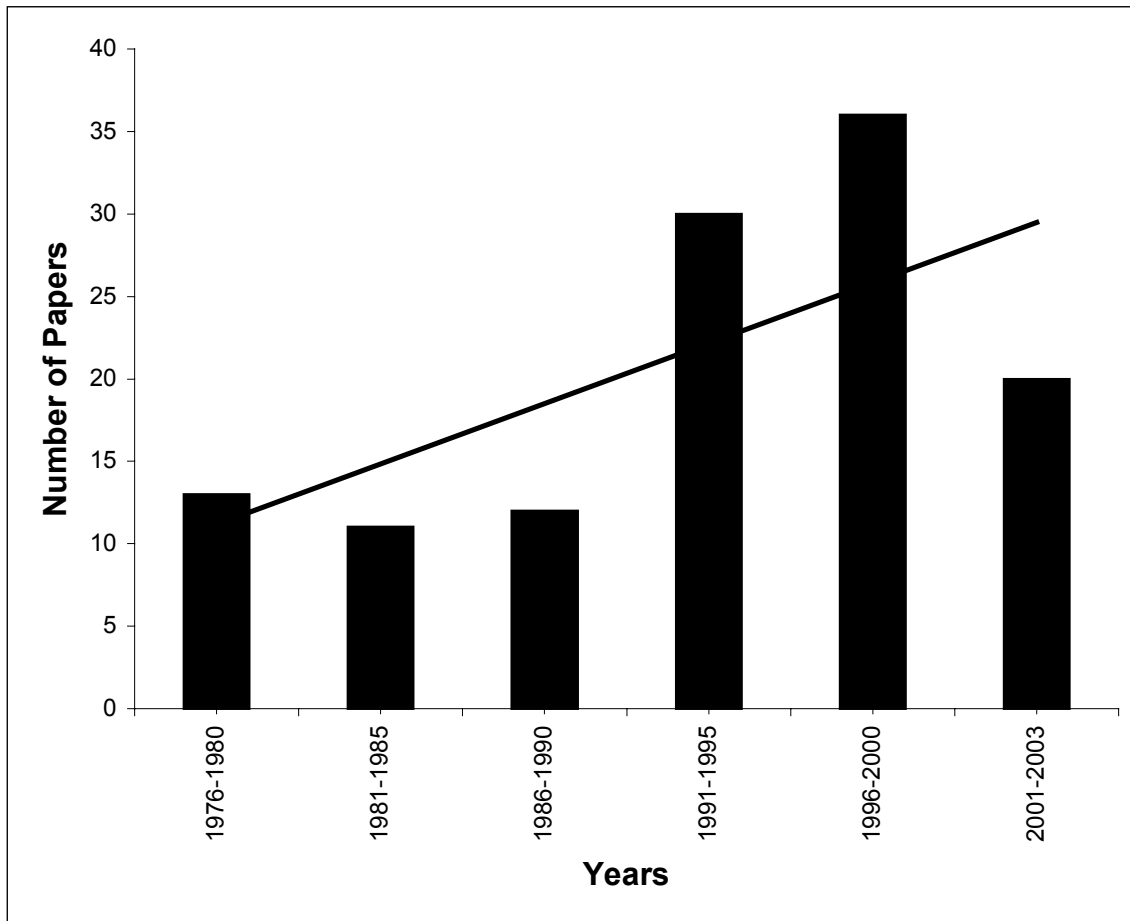


Figure shows the increasing application of foraminifers for pollution monitoring studies based on collection of published reports taken from ASFA and Sciencedirect search along with some of the journals in which studies involving application of foraminifers are commonly published.

Table 1: Examples of studies mentioning application of foraminifers for pollution monitoring

Author	Year	Pollutants (Source/Type)	Remarks
Zalesny, E. R.	1959	sewage outfall	Increase in total population near outfall region. <i>Trochammina pacifica</i> is more.
Resig, J.M.	1960	Sewage outfalls	Foraminiferal abundance and species diversity decreased while number of araneose species increased.
Watkins, J.G.	1961	Sewage outfall	Foraminiferal abundance increases; abnormal tests are common in <i>Elphidium spinata</i> and <i>Nonionella basispinata</i> . Outfall has little effect on size.
Bandy, O., Ingle Jr., J.C. and Resig, J.M.	1964	Sewage aureole	Hyaline, calcareous perforate and planktonic foraminifers increased near the aureole; <i>Bulimina elegantissima</i> and <i>Buccella frigida</i> are abundant.
Bandy, O., Ingle Jr., J.C. and Resig, J.M.	1964	Sewage aureole	Planktonic to benthic ratio is high near the outfall; <i>Bulimina marginata denudata</i> , <i>Buliminella elegantissima</i> and <i>Discorbies columbiensis</i> are dominant; <i>Nonionella</i> is adversely affected by outfall.
Bandy, O., Ingle Jr., J.C. and Resig, J.M.	1965	Sewage aureole	<i>Bulimina marginata denudata</i> , <i>Buliminella elegantissima</i> are 10-5000 times more abundant near the outfall. <i>Nonionella</i> is unfavorably influenced.
Bandy, O., Ingle Jr., J.C. and Resig, J.M.	1965	Sewage aureole	Calcareous perforate foraminifera increased as <i>Bulimina marginata denudata</i> , and <i>Buliminella elegantissima</i> ; <i>Nonionella</i> decreases towards the outfall.
Seiglie, G.A.	1968	Organic carbon content	High organic carbon content results in specific foraminiferal assemblage.
Schafer, C.T.	1973	Sewage and (or) industrial effluent	Species diversity varies as per the distance from the outfall; <i>Elphidium incertum/clavatum</i> usually dominates the live fauna near the outfalls.
Banerji, R.K.	1974	Ocean outfalls	Application of benthic foraminifers to distinguish polluted environments.
Rao, K.K.	1974	High organic carbon content	High organic carbon content results in low species diversity and increased abundance of <i>Ammonia beccarii</i> group and araneose foraminifera.
Schafer, C.T., Wagner, F.J.E. and Ferguson, C.	1975	Organic carbon and metals from heavy water plant and pulp mill	Foraminifers have comparatively higher tolerance; <i>Elphidium advena</i> , <i>Elphidium incertum</i> and <i>E. clavatum</i> are abundant near the pollution source.
Setty, M.G.A.P.	1976	Effluents from fertilizer industry	<i>Ammonia</i> sp. and its variants are abundant; <i>Nonionella</i> sp. adversely affected.
Bates, J.M. and Spencer, R.S.	1979	Sewage outfall	Live foraminifera increases away from the outfall; <i>Buccella frigida</i> and <i>Elphidium excavatum</i> are more near the outfall.
Rao, K.K. and Rao, T.S.	1979	Effluents from metal industry	Solution effect and decreased species diversity near the outfall.
Setty, M.G.A.P.	1982	Industrial effluents and organic matter	Living foraminifers absent in polluted areas; dead ones are small, thin walled highly corroded and without ornamentation.
Govindan, K., Varshney, P.K. and Desai, B.N.	1983	Effluents from Industries	Benthos is badly affected by the industrial pollution.

- Setty, M.G.A.P. and Nigam, R. 1984 Acidic and alkaline effluents from fertilizer and metal industry. Pollutants cause reduction in size, lower than normal ornamentation and abnormalities in test.
- Naidu, T.Y.; Rao, D.C.; Rao, M.S. 1985 Anthropogenic activities. Foraminifers can be used to detect adverse effects of pollutants.
- Alve, E. and Negy, J. 1986 Effluents from paper mill, farm land and domestic sewage. Agglutinated foraminifers are abundant while calcareous species are affected by dissolution.
- Bhalla, S.N. and Nigam, R. 1986 Ammonia and arsenic from the fertilizer industries. Increased abundance of foraminifers and abnormality in the tests of *Ammonia* from polluted areas.
- Ellison, R.L., Broome, R. and Ogilvie, R. 1986 Zn, Cr and V from industrial and municipal waste. *Ammobaculites crassus* abundant at the edge of polluted region.
- Madabhushi, S. 1989 Industrial effluents. *Bolivina* and *Ammonia* are more tolerant to industrial effluents.
- Madabhushi, S. 1989 Pollution from solution of limonite and goethite. Abundance of pyritized tests was used to infer pollution from active solution of limonite and goethite.
- Alve, E. 1991 Heavy metals. *Verneuilina media* and *Eggerelloides scabrus* assemblage represent moderately and extremely polluted environment respectively. Pollution results in abnormal and pyritized specimens.
- Boltovskoy, E., Scott, D.B. and Mediolli, F.S. 1991 All kinds of wastes. The effect of pollution on the size and morphology of the foraminifers is difficult to understand because of the paucity of the literature available.
- Schafer, C.T., Collins, E.S. and Smith, J.N. 1991 Organic matter discharges from pulp and paper mills. *Spiroplectamina biformis* were absent from polluted areas at certain times as a consequence of pollution stress.
- Sharifi, A.R., Croudace, I.W. and Austin, R.L. 1991 Heavy metals. Deformed specimens contain higher level of Cu and Zn than normal specimens.
- Banerji, R.K. 1992 Metallic ions from all kinds of industrial and urban waste. Species diversity is more in sediments with Fe-Mn-Zn and less in Co-Ni-Pb. Lagenids are least affected while *Elphidium* group of species are most affected.
- Moodley, L., Troelstra, S.R. and Vanweering, T.C.E. 1993 Increased supply of degradable organic matter. The general increase in biomass and densities of macrofauna has been attributed to an increased supply of degradable organic matter to the sediment.
- Yanko, V., Kronfeld, J. and Flexer, A. 1994 Coal, heavy metals and domestic sewage. Foraminiferal tests were smaller, often stunted and frequently pyritized.
- Barmawidjaja, D.M., Van der Zwaan, G.J., Jorriksen, F.J. and Puskarić, S. 1995 Agriculture and waste water disposal. Variations in anthropogenic activities are reflected in benthic foraminiferal patterns.
- Bresler, V. and Yanko, V. 1995 Cadmium, copper, and mercury. Toxicity of cadmium, copper, and mercury to the benthic epiphytic foraminifera *Pararotalia spinigera* (Le Calvez) was investigated.
- Alve, E. 1995 Organic flux from saw mills, First record of agglutinated dominated assemblages bordering anoxic

- paper and pulp industry, agricultural drainage and domestic sewage
- environments. *Stainforthia fusiformis* most successful species to colonize formerly anoxic environments.
- 1995 Alve, E. and Murray, J.W. The abundance of foraminifera is related to the fertility of the area.
- 1995 Collins, E.S., Scott, D.B., Gayes, P.T. and Medioli, F.S. Near shore localities show the effects of combined organic matter pollution and high riverine discharge.
- 1995 Culver, S.J. and Buzas, M.A. Summarized potential effects of increasing environmental stresses on the foraminifers.
- 1995 Schafer, C.T., Winters, G.V., Scott, D.B., Pocklington, P., Cole, F.E. and Honig, C. Living foraminifers are severely affected by the higher concentrations of organic matter from marine aquaculture operations
- 1995 Williams, H.F.L. Foraminiferal assemblage is affected
- 1996 Venkatachalapathy, R., Hussain, S.M and Ragotham, V. Pollution results in corrosion, enlargement of pores, widening of apertures in the foraminiferal tests
- 1996 Jayaraju, N. and Reddi, K.R. Pollution causes reduced diversity and population. Reduction in size followed by test wall thickening in *Ammonia* and *Florilus*.
- 1998 Geslin, E., Debenay, J.-P. and Lesourd, M. Introduction of alien trace elements may cause crystalline disorganizations and cavities in the wall.
- 1998 Yanko, V. and Ahmad, M. and Kaminski, M. Morphological deformities of tests appear to be sensitive *in situ* monitors of marine pollution by heavy metals.
- 1999 Alve, E. Reviewed the processes governing benthic foraminiferal dispersion and colonization patterns in modern environments.
- 1999 Brewster-Wingard, G.L. and Ishman, S.E. The effects of anthropogenic activities are reflected in the foraminiferal characteristics.
- 1999 Yanko, V., Arnold, A.J. and Parker, W.C. The variation in abundance of foraminifers in response to pollutants is not well understood; laboratory culture experiments and cytological studies are needed.
- 2000 Angel, D.L., Verghese, S., Lee, J.J., Saleh, A.M., Zuber, D., Lindell, D. and Symons, A. Abundance highest in the "hypertrophic" zone. No clear indicator species of organically enriched benthos. Deformed tests could,nt be attributed to pollution.
- 2000 Debenay, J.-P., Tsakiridis, E., Soulard, R. and Grosseil, H. Polluted sediments near the careening areas are indicated by tolerant pioneer species *Cribroroeplidium ecaevatum* and *Hynesina germanica*.

Halloock, P.	2000	Anthropogenic activities	Ultraviolet radiation affects symbiont-bearing foraminifera leading to calcification and reproduction anomalies; increased susceptibility to infestation and predation
Naidu, T.Y., Kesavakumar, G.V. and Rama Krishna, B.	2000	Industrial waste, exhaust of oil from ships and domestic sewage	Benthic foraminifera respond negatively at the site of high intensity of pollution.
Samir, A.M.	2000	Heavy metals (Pb, Zn, Cu, Cr and Cd), ammonia and organic matter from anthropogenic activities	Benthic foraminifera more sensitive to heavy metals than to agricultural wastes. <i>Ammonia beccarii</i> forma <i>parkinsoniana</i> less resistant to pollution than forma <i>tepida</i> . Benthic foraminifera less tolerant to pollution than ostracodes and molluscs.
Debenay, J.-P., Geslin, E., Eichler, B.B., Duleba, W., Sylvestre, F. and Eichler, P.	2001	Human Impact	Morphological abnormalities could not be attributed to anthropogenic stress. However, the <i>Ammonia tepida</i> is probably affected by human impact.
Samir, A.M. and El-Din, A.B.	2001	Industrial agricultural and domestic wastes, chiefly heavy metals (Pb, Zn, Cu, Cr, and Cd),	Pollution results in low species diversity and population density, while increase in tolerant or opportunistic species, and abundance of stunted and aberrant tests.
Geslin, E., Debenay, J.-P., Duleba, W. and Bonetti, C.	2002	Sewage, oil heavy metals and pesticides	The relative abundance of abnormal tests used as a bio-indicator of pollution must be handled with care.
Alve, E.	2003	All kinds of wastes	The opportunistic life-strategy of <i>Stainforthia fusiformis</i> makes it highly adapted to cope with environmental stress.
Eilberling, B. Knudsen, K.L., Kristensen, P.H. and Asmund, G.	2003	Heavy metals from sulphidic mine waste.	Abnormalities among foraminifera may represent a useful biomarker for evaluating trends in the biological impact.
Ward, J.N., Pond, D.W. and Murray, J.W.	2003	Sewage derived particulate organic matter	Lipid biomarker analysis indicated that <i>Haynesina germanica</i> did not consume secondary treated sewage-derived POM.
Châtelet, E.A., Debenay, J.-P. and Souillard, R.	2004	Heavy metals and polycyclic aromatic hydrocarbons (PAH)	Foraminiferal density and species richness of the assemblages decrease with an increase in heavy metal and PAH concentration

Table 2: Studies mentioning application of foraminifers for temporal variation of pollutants

Author	Year	Pollutants (Source/Type)	Remarks
Schafer, C.T.	1982	Organic matter and cadmium	Population and diversity increased after the cessation of dumping activity.
Nagy, J., and Alve, E.	1987	Paper mill, agricultural effluent and domestic waste	Temporal variation in total population, relative frequency of calcareous and arenaceous foraminifera and species composition.
Schafer, C.T., Collins, E.S. Smith, J.N.	1991	Organic matter discharges from pulp and paper mills	Foraminifers responded positively to the decrease in concentration of pollutants.
Grant, J., Hatcher, A., Scott, D.B., Pocklington, P., Schafer, C.T. and Winters, G.V.	1995	Mussel feces and pseudofeces from suspended mussel culture	Foraminiferal species composition showed a temporal response to temperature changes in the cove by shifting toward calcareous species, but assemblages down core showed little or no relationship to aquaculture impacts.
Scott, D.B., Schafer, C.T., Honig, C. and Younger, D.C.	1995	Fish food and fecal material	Temporal variation of foraminifera suggests little environmental impact.
Cockey, E., Hallock, P. and Lidz, B.H.	1996	Nutrient flux	Time series data for foraminiferal characteristics can be used to monitor pollution.
Stott, L.D., Hayden, T.P. and Griffith, J.	1996	DDT and solid waste from sewage outfall	<i>Nonionella</i> spp. should provide good indication of conditions around other environmentally sensitive regions along the California coast.
Geen, A.V., Luoma, S.N.	1999	Cd from agriculture discharge	Cd/Ca ratio of foraminifers is directly proportional to agriculture discharge
Cearreta, A.M., Irabien, M.J., Leorri, E., Yusta, I., Croudace, I.W. and Cundy, A.B.	2000	Untreated industrial and domestic effluents.	Variation in foraminiferal assemblage indicates persistence of environmental degradation.
Karlsen, A.W., Cronin, T.M., Ishman, S.E., Willard, D.A., Holmes, C.W., Marot, M. and Kerhin, R.	2000	Fresh water flow and nutrients from the water shed area	Since the 1970s, deformed tests of <i>A. parkinsoniana</i> occur in all cores (10-20% of <i>Ammonia</i>), suggesting unprecedented stressful benthic conditions.
Thomas, E., Gapotchenko, T., Varekamp, J.C., Mecray, E.L. and ten Brink, M.R.B.	2000	Nutrient input by wastewater treatment plants	Decrease in relative abundance of <i>Elgerella advena</i> , increase in relative abundance of <i>Ammonia beccarii</i> , and decrease in species diversity.
Cearreta, A.M., Irabien, M.J., Ulibarri, I., Yusta, I., Croudace, I.W. and Cundy, A.B.	2002	Anthropogenic fluxes of Zn, Pb, Cu and As	Temporal change in foraminiferal assemblage and abundance of few species as a result of variation in anthropogenic pollution.

Leduc, J., Bilodeau, G., de Vernal, A. and Alfonso, M.	2002	Pulp and paper mills	The decrease of <i>Spiroplectammina biformis</i> with increase of organic matter in the sediments because of reduced industrial discharges.
Nigam, R., Nayak G.N. and Naik S.	2002	Increased suspended load from mining activities	Decline in total foraminiferal number and species diversity.
McGann, M., Alexander, C.R., Bay, S.M.	2003	Sewage discharge	Foraminifers positively respond to the changed sewage outfall and can be used as efficient tool for temporal variation of pollution history
Ruiz, F., Regalado, M.L., Borrego, G.-J., Abad, M. and Pendon, J.G.	2004	Acidic waste and trace metals from fertilizer, petroleum and chemical industries	Almost total disappearance of ostracodes and foraminifers during the industrial period.

Table 3: Culture studies in support of application of foraminifers for pollution monitoring based on field studies

Author	Year	Pollutants (Source and type)	Remarks
Bradshaw, J.S.	1961	Hydrochloric acid, penicillin and streptomycin	<i>Ammonia beccarii tepida</i> is highly resistant to pH and also that antibiotics cause decreased growth and increased mortality.
Angell, R.W.	1967	Hydrochloric acid	Showed capability of <i>Rosalina leei</i> to regenerate its test after dissolution under acidic condition
LeFurgey, A. and Jean, J.S.	1976	Sewage effluents	Species diversity was approximately 20 percent higher and average number of living foraminifera was approximately 5 times greater in control ponds than in the effluent ponds.
Cantelmo, F.R., Tagatz, M.E. and Rao, K.R.	1979	Barite, a constituent of drilling mud	Foraminifera didn't show any significant effect of introduction of barite.
Bresler, V. and Yanko, V.	1995	Natural organic compounds (UNOC) derived from decomposed seaweeds, heavy metal ions and three tracer xenobiotics, acridine orange, neutral red and fluorescein	The presence of UNOC in seawater decreased acute toxicity of heavy metal ions for foraminifera.
Moodley, L., Schaub, B.E.M., Van der Zwaan, G.J. and Herman, P.M.J.	1998	Hydrogen sulphide	Tolerance of sulphidic conditions was restricted to survival and that sulphide may be a prominent distributional factor for benthic foraminifera.
Alve, E. and Olsgard, F.	1999	Copper	Not even sediment [Cu] greater than 2000 ppm had a severe negative impact on the foraminiferal species ability to colonize.
Gustafsson, M., Dahlhof, I., Blanck, H., Hall, P. Molander, S. and Nordberg, K.	2000	Tri-n-butyltin (TBT)	TBT affects the foraminiferal community
Cadre, V.L., Debenay, J.-P. and Lesourd, M.	2003	Hydrochloric acid	Short-term acidification, resulting in dissolution of test, can give rise to abnormalities in the test during recalcification.
Saraswat, R., Kurtarkar, S.R., Mazumder, A. and Nigam, R.	2004	Mercury	Presence of mercury in the ambient environment causes decreased growth rate, smaller final size and abnormalities in <i>Rosalina leei</i> .