

Limits in Predicting and Detecting Benthic Community Responses to Manganese Nodule Mining*

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Abstract There are severe problems both in predicting and in detecting the responses of benthic communities to manganese nodule mining. Predictions are hampered by the basic lack of natural history information for deep-sea organisms; in all but a few instances, crucial data on dietary habits, population dynamics, modes and rates of dispersal, food-web relationships, and natural successional sequences and rates are lacking. Detection is further impeded by sampling problems. Besides the obvious logistic problems encountered in sampling under miles of water, the extremely low areal densities at which most deep-sea species live enforce wide confidence limits about their estimated mean abundances. The rarest species in any deep-sea community have yet to be sampled.

Nonetheless, some predictions can be made. Animals in the path of the nodule collector will suffer high mortalities. Populations dependent upon manganese nodules as attachment substrata will be very slow to recover ($> 10^3$ yr), as will food-web members dependent on this encrusting epifauna. Mobile scavengers (i.e., fishes, amphipods,

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and shrimps) will find a new, temporary food source in the form of injured and displaced animals, but they may be forced to switch to carnivory when a given mining effort ceases. Suspension and surface deposit feeders will be most heavily impacted by mining-induced resuspension and redeposition, the extent of this effect depending on the (unknown) food value of the resuspended material. Substantial narrowing of uncertainty in mining effects, however, will require continuing iteration among predictive ecological modeling, *in situ* experimentation, and carefully designed monitoring of actual, full-scale mining operations.

The aim of this paper is, within the realm of conceivable impacts of manganese nodule mining, to identify the somewhat smaller region of likely responses within deep-sea benthic communities. From the outset, I will set the limits of resolution at the level of effects leading to the appearance or disappearance of individuals, to actual changes in community composition. Physiological changes that are not likely to lead to altered population birth or mortality rates will not be addressed. I hope to make two problems apparent: one is the shortage of verified theory concerning deep-sea community structure, and the other is the imprecision with which deep-sea community spatial structure and changes in it have been and can be measured. To accomplish these goals within a limited space, I will draw freely upon several recent, more specialized, yet more comprehensive reviews. Rather than redescribing the biota of the DOMES area, I will rely on the extensive baseline of Hecker and Paul (1979). Pertinent theory regarding the mechanisms controlling deep-sea community structure will be abstracted from Jumars and Gallagher (1981), while conclusions about spatial structure and sampling variability within deep-sea communities will be extracted from Jumars and Eckman (1981). Comments on conservation strategies largely will reflect the landmark collection on this topic by Soulé and Wilcox (1980), although opinions on optimal procedures are far from unanimous.

While the lack of verified theory and of data on deep-sea community structure is serious, it does permit straightforward presentation of this chapter. In a "connect-the-dots" approach to outlining the likely outcomes of mining, I will simply present contrasting scenarios of likely results. Following the more detailed, and less specific to manganese nodule mining, approach of Jumars and Gallagher (1981), I will choose

dots or pairs of dots at the individual, population, and community levels of ecological organization. I sincerely hope that neither member of the respective pairs will be extracted from context and considered alone. If the approach is sound, it will serve to box in the effects that require controlled experimentation and monitoring as mining proceeds. The size of the box alone attests that monitoring and experimentation will be needed to determine where (hopefully) within this figure the truth will lie.

I will endeavor not to make value judgments, but policymakers may find it difficult to form such evaluations without familiarizing themselves with the kinds of organisms that frequent the deep sea. Contrary to the plates in volumes describing early voyages of discovery, the numerically dominant members of the deep-sea benthic community are tiny (a few millimeters or less in length) nematode and polychaete worms and test-building protozoans (Foraminifera) of varying sizes (but again mostly smaller than a few millimeters in diameter). Most of these animals inhabit the uppermost centimeter of deep-sea sediments. More thorough and less diminutive illustrated descriptions can be found in Gage (1978), Grassle (1978), Hessler (1972), Hessler and Jumars (1974), and Jumars and Gallagher (1981). Many of the surprisingly numerous species are as yet not even described, much less well known; so that it clearly is impossible to estimate how valuable these organisms might someday become, for example as sources of natural pharmaceuticals (e.g., the once nearly worthless horseshoe crab) or as model systems for addressing scientifically and medically important questions (as sea urchins have been in studying fertilization and early embryonic development). Because the smaller species (meiofauna and microbiota) are so poorly known, I will limit my discussion to those species that are (if only barely) visible to the naked eye (i.e., macrofauna and megafauna).

Because the questions of tightness of organization and interdependency of the various components of communities are still matters of debate, even for much more accessible communities (e.g., Levin, 1975), it is worth attempting prediction of several levels of ecological organization. The truth falls somewhere between the extreme view that a community can be understood simply by summing the behaviors of its smallest component parts (individuals, at the aforementioned level of resolution) and the opposing view that the interactions among these

parts are so strong that communities can be understood only by studying the whole. Numerical abundances given below, unless otherwise stated, are quoted from the extensive baseline studies of Hecker and Paul (1979) in the DOMES region. Mining rates are taken from Ozturgut *et al.* (1981, Appendix).

Likely Impacts

Individual Level

It is hardly worth arguing about the fate of individuals directly in the path of the nodule collector. Those that are not killed outright by the fluid shear produced in the dredge or by the combination of abrasion and temperature rise in traveling up the pipe will be ejected helter-skelter with sediments in the near-bottom plume. Technical difficulties, including ones of experimental design, would argue against attempting to monitor whether mortality amounts to 95% or 99.999% of the total individuals taken. With 168 (macrofaunal) individuals per m² and assuming 100% mortality, that amounts to 3.36×10^3 individuals per second, 2.9×10^8 per day, or 1.06×10^{11} individuals per mining ship per year. At roughly 0.3 g of wet weight per m², that equates with 1×10^8 g per year.

From this point, predictions become decidedly less precise. Impacts on individuals outside the collector zone surely will depend upon the guild to which they belong—upon their life-styles. (An ecological guild is defined as a group of species that utilizes the same resource in similar ways.) Specifically, impacts on swimming scavengers, walking-crawling scavengers, surface deposit feeders, subsurface deposit feeders, and suspension feeders are likely to differ.

The scavengers are the most active lot, and the fishes, shrimps, and larger lysianassid amphipods are likely to be able to avoid local regions of high redeposition rates and high turbidity. The non-swimming scavengers observed to date are among the larger benthos, so we might expect them to be relatively immune from mortality due to burial. Both kinds of scavengers are likely to experience a short-term increase in rate of food supply in the form of animals injured by mining, with the swimming forms obviously being first to arrive at the windfall.

Subsurface deposit feeders are likely to be the least affected of all

feeding guilds on the short term because of their relative isolation from re-sedimentation effects. Presumably they are dependent upon continued bacterial growth for their food, and it is not known how subsurface bacterial growth will vary as a function of time and thickness of the overlying re-sedimented layer. Because of the low standing stocks of animals, the scavenger activity, and the high concentration of oxygen in bottom water, there seems to be little opportunity for anaerobic conditions to develop, even for the subsurface dwellers; no mass mortality due to anoxia is anticipated.

Surface deposit feeders and suspension feeders, on the other hand, will be affected much sooner and perhaps in similar ways. The rate of supply of surface deposits and of suspended material certainly will be increased, but its net food value is likely to be altered substantially over the normal surface deposit and suspended load. Very little is known about the organic chemistry of deep-sea clays under deep-sea conditions, but adsorption of materials onto suspended clays may be a major effect (e.g., Moore, 1977). If the average food value of these resuspended and redeposited particulates is still lower than that of their normal supplies, then the net rate of energy gain to members of surface deposit-feeding and suspension-feeding guilds is likely to fall. It is conceivable, alternatively, that the net rate of energy gain within these guilds might be increased if, during resuspension, the clays chemically scavenge sufficient organic matter from the overlying water.

Assuming no fatality beyond the collector path, Figure 1 summarizes these predictions of net rates of energy gain by individuals within various guilds. How likely is fatality? If net rate of energy gain falls below maintenance levels for an appreciable period, mortality would result. I find little basis for predicting the actual time scales in Figure 1, except that suspension feeders will be affected only so long as the cloud of resuspended material remains in their vicinity or so long as their feeding mechanism remains affected. Deep-sea suspension feeders are likely to be especially sensitive to clogging of their filtration apparatus, which after all has evolved to operate at ambient suspensate levels of a few micrograms per liter; even 20 km from the mining site, suspensate levels may rise by two orders of magnitude (Ozturgut *et al.*, 1981).

Burial under a few centimeters of sediment may seem and be innocuous enough to one accustomed both to the large amounts of sediment transport and to the strong burrowers often seen in the intertidal. Most

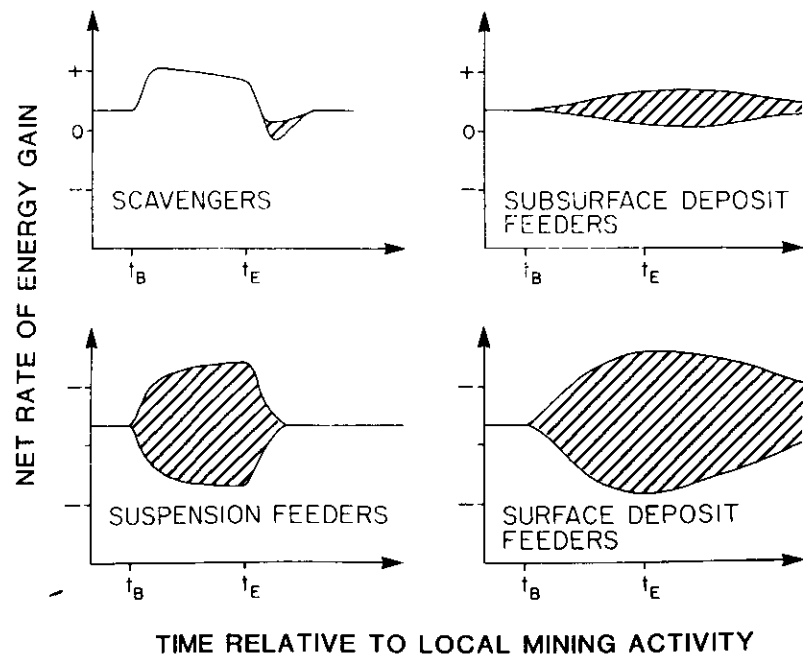


FIGURE 1. Crude predictions of net rate of energy gain as a function of time by feeding guild for those individuals (as opposed to populations) not suffering immediate mortality from mining effects. t_B : local mining begins; t_E : local mining ends; shaded area: major region of uncertainty in predictions. Predictions at the level of numerical responses of populations are more difficult.

deep-sea animals living near the sediment–water interface of nodule fields have limited burrowing abilities, however, because sedimentation proceeds at rates of millimeters per 10^3 yr. In an accidental burial of a small region (~ 10 m²) of a bathyal community living at 1,200 m (where sedimentation rates are roughly 10 cm per 10^3 yr), for example, I have observed substantial mortality (unpublished observations of an unsuccessful particle tracer experiment attempted during Expedition Quagmire; Thiel and Hessler, 1974) of numerous sedentary animals after only one day's burial. Suspension feeders were too rare to be censused with adequate statistical precision, but most of the mortality was evident (as autolysis or bacterial decay) in surface deposit feeders. Although linear extrapolation is hazardous at best, these results suggest that burial depths of millimeters may cause substantial mortality among the faunas of the DOMES area. For animals adapted to feeding at the sediment–water interface, it is conceivable that burial of their normal food resources under a millimeter or less might be critical, depending on the time scale over which these food resources recover. The sessile suspension feeders attached to nodules are likely to be the most severely affected, however, even by an exceedingly thin veneer of sediments.

Population Level

Two extreme views are tenable at the population level. One of them may prove true generally, or each may hold for some subset of the populations encountered. The most optimistic view would hold that little mortality would ensue outside the collector tracks, so that in a year some 170 km² of the 30-km by 30-km mining claim would remain inhabited by members of the population. If they were not completely sessile, these survivors would begin to diffuse to produce something like 80% of their initial areal density. (A majority of abyssal species seem to be slowly moving deposit feeders; Hecker and Paul, 1979; Hessler and Jumars, 1974.) If this density is high enough for reproductive success, recruitment will complement the diffusive recovery. If, on the other hand, the population were completely eliminated within the mining claim and for some distance outside it, recruitment to the center of the site would require either many generations of slow, diffusion-like movement or some more rapid means of adult, juvenile, or larval dispersal. Given the seemingly low dispersal abilities of the majority of deep-sea species,

this case likely would resemble the slow healing of a deep wound, while the more optimistic first case would be more like the healing of a series of scratches.

To carry this metaphor perhaps too far, both cases are likely to result in "infection" by opportunistic species. Within months, azoic sediments placed on the sea floor in the deep sea are colonized by populations with high dispersal abilities. In the two experimental programs whose results have been published to date (Grassle, 1978; Desbruyères *et al.*, 1980), the most spectacularly successful initial colonists are species that are either absent or very rare in the ambient, undisturbed community.

It is thus reasonable to anticipate a strong, mining-produced selection for high dispersal abilities, coupled with relatively rapid reproductive rates, to fill the gaps produced by the tracks or by the combination of tracks plus resedimentation. In essence, one expects a suite of weed species to recruit to, and to evolve with, the mining activity. Beyond the edges of the mining site, however, selection may favor rather different life-history tactics. Suppose, for example, that the resedimentation near the periphery causes greater or more variable mortality in larvae and juveniles than in adults. Jumars and Gallagher (1981) summarize a simple stochastic model which suggests that, under such circumstances, selection will act to lengthen the less susceptible adult life stage and to lead toward multiple reproductive events (iteroparity), features normally not associated with populations of stressed or disturbed habitats.

Besides varying with proximity to the disturbance, population responses probably will also depend on the feeding guilds under consideration. I already have mentioned the rapid functional response of scavengers to deep-sea windfalls. Especially because of the relative continuity of this new food resource, mining is likely to result in a numerical (reproductive) response as well. Given the high motility of many deep-sea scavengers, though, this numerical response may be especially difficult to resolve from pure attraction. But what will these locally elevated (in abundance) populations do when mining ceases? For energetic reasons suggested by Jumars and Gallagher (1981), this guild is likely to be comprised of generalists which may survive by a combination of dispersal and carnivory when mining ceases.

Much less likely to be so malleable are the populations dependent on nodule-associated microhabitats for their existence (e.g., Bernstein *et*

al., 1978). Most obviously, the fouling community of nodule surfaces will probably suffer most and longest. Simply because of the slow growth rates of deep-sea manganese nodules and the fact that nodules will be both removed and buried, these populations are unlikely to recover to natural levels in less than 10^4 yr. Time scales for recovery of other populations cannot be predicted because generation times of nearly all deep-sea species are unknown.

Community Level

Implicit in many of the above population-level effects is the potential for interpopulation interactions. Will the scavengers have substantial predatory impacts on particular prey populations after the source of easier game is removed? Will subsequent invasion of the newly opened territory be facilitated, unaffected, or impeded by the initial colonists (Connell and Slatyer, 1977)? If populations of suspension and surface deposit feeders are reduced, will burrowing deposit feeders encroach on food resources that would have been taken by these two guilds? Very basic natural history information is needed to answer these questions regarding the precise nature of the resources now used by suspension and deposit feeders and the identity of existing predatory-prey links. These data are missing for all deep-sea areas.

The value of this lacking information can be seen by analogy with the diverse communities of tropical rain forest, where at least part of such information has been collected. Gilbert (1980, p. 32), for example, finds that "The system consists of many parallel, structurally similar but taxonomically different, food webs based on particular groups of plants." Similar organization also seems likely in the deep sea, and while it may seem reasonable to predict that predators dependent upon nodule-associated prey will be impacted seriously, this prediction is vitiated because the predators have not been identified, and thus their abilities to utilize alternate prey are completely unknown.

A theme reiterated throughout the anthology by Soulé and Wilcox (1980), *Conservation Biology*, is the need to know the sources, rates, and intensities of natural disturbances in order to predict and manipulate the effects of anthropogenic disturbances. Further, the less similar are these two types of disturbances (if the more frequent and severe type is anthropogenic), the more severe will be the effects of the man-made

variety. No natural disturbance of the magnitude to be produced by full-scale mining has been identified for communities of geologically stable mid-ocean regions; all conceivable natural disturbances are much smaller in spatial scale (Jumars and Eckman, 1981) and presumably are less intense.

There is no validity whatsoever, then, in examining community structure and life-history tactics of communities that are exposed relatively frequently to major disturbances such as turbidity flows and using them (Gerard, 1976) to predict the short-term consequences of nodule mining. The comparison is just as ludicrous as suggesting that tropical rain forest will respond to a blizzard in the same way as will tundra. If mining continues at an appreciable rate, selection may lead in the direction followed in areas where turbidity flows are frequent and severe, but this would be a long-term (evolutionary time scale) prediction. Even on this longer time scale, the analogy is imprecise because any one mining plot likely will be mined only once and because the native sediments of nodule areas and continental margins (where turbidity flows are more common) differ substantially.

The events following mining also are difficult to put into the context of the most recent synthesis of successional theory (Connell and Slatyer, 1977). Beyond the suggestion (above) that opportunists will recruit to the mined region within one or a few months, neither the time scales nor the specific directions of succession can be predicted. The initial colonists may alter environmental conditions (e.g., effective sediment porosity and permeability), either accelerating or impeding subsequent colonization, and the initial colonists may be removed via predation, competition, or their own modifications of the sediments. No deep-sea colonization experiments reported have yet shown close approach to the ambient community composition. Given the apparently long lifetime of some deep-sea, sediment-dwelling species (e.g., Turekian *et al.*, 1975), such nearly complete recovery would take decades to tens of decades. Again, simply because of the slow growth rates of nodules, any community components dependent directly or indirectly upon nodules would take more than 10^3 years to begin approaching natural abundance levels in the area of the collector track.

A wide variety of theories dealing with succession and (dynamic) equilibrium community composition lead to similar predictions (Figure 1) concerning the relation of species diversity with the frequency and

intensity of disturbance. Both of the two extreme Markov models presented by Jumars and Gallagher (1981), for example, predict a relationship like that of Figure 2. While it seems likely, especially given removal of the nodule microhabitat, that mining at the proposed levels will drive the curve toward the lower diversities of its right-hand tail, the position of the natural community along the abscissa is unknown. Extant theories (Jumars and Gallagher, 1981) differ substantially in the importance, frequency, and intensity they ascribe to such natural disturbances as predation and windfalls of food.

It is possible, then, that some low level of mining activity might actually increase species diversity on an appropriately measured spatial scale. The simplest such scenario is that in which opportunistic species (new to the local community) take up residence in the tracks of the dredge, and the community outside the tracks is unaffected, increasing local community diversity by the difference between the number of new opportunistic community members and the (small) number of species that chanced to be present locally only in the path of the dredge. Considering the magnitude of the disturbance (relative to natural ones), a much more likely scenario, however, involves a dramatic local decrease in species diversity. Besides the obvious disturbance effect (*viz.*, Figure 2), a correlate and possible cause of high deep-sea species diversity is small-scale environmental heterogeneity (*e.g.*, tubes and burrows) created by the animals themselves (Jumars and Gallagher, 1981). The net effect of nodule removal and burial of the surrounding bottom of resedimenting clay would almost surely be to make the new environment more homogeneous on these smaller spatial scales.

Extrapolation to Multiple Mining Sites

Implicit in all the above predictions is their limitation to a single mining site approximately 30 km by 30 km in area, mined for a topical mining year (estimated at 300 days). The impossibility of extrapolating these predictions with any set accuracy to multiple mining sites needs to be pointed out. The ability to make analogous extrapolations is just now being approached in the obviously much better known forest ecosystems through successional models (summarized by Shugart and West, 1980). Such models are heavily dependent upon detailed autecological information—detail unavailable in the deep sea.

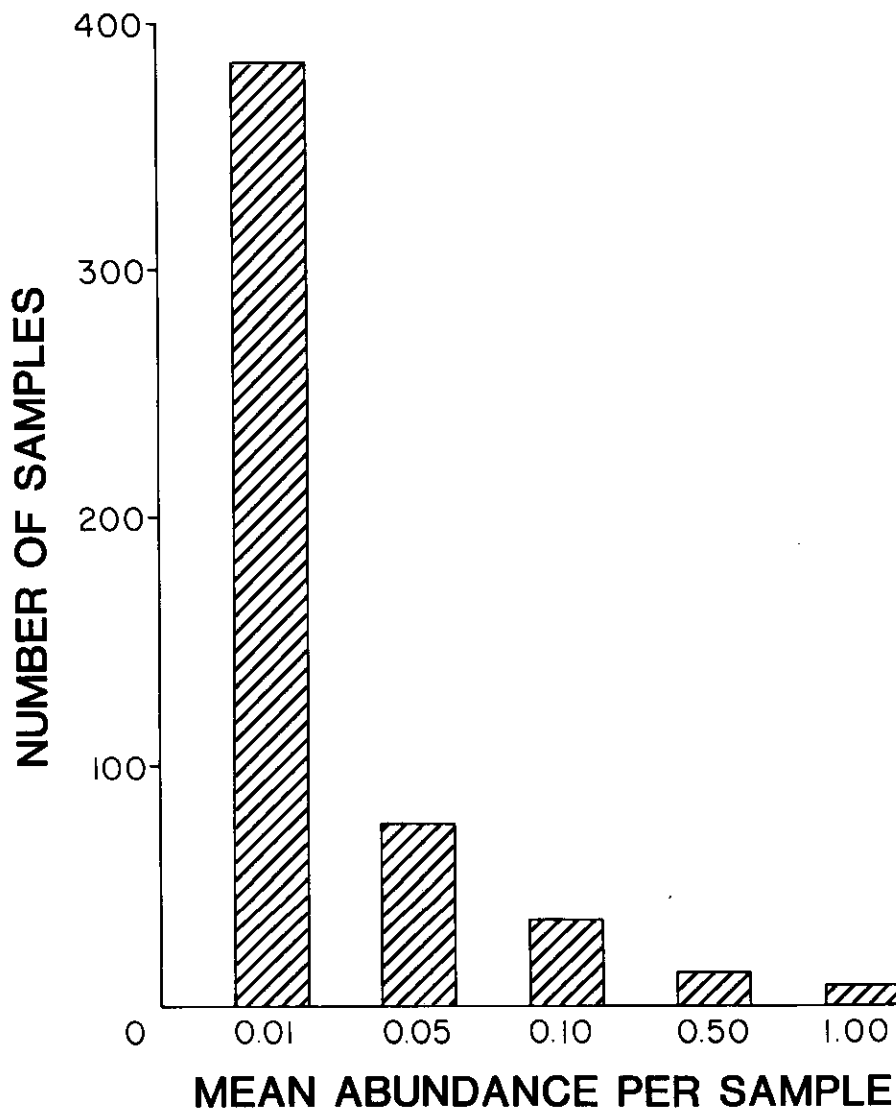


FIGURE 2. General predictions from a wide diversity of models (e.g., Horn, 1975; Huston, 1979; Levin and Paine, 1975) concerning the species diversity likely to result from different rates of mortality-causing disturbances. Without manipulations (cf. Paine, 1977) such as carefully monitored mining, the position of natural deep-sea communities along the abscissa will remain unknown.

One concern that already has surfaced is over the potential extinction of deep-sea populations and species at some (perhaps unrealistically high, but unknown) level of mining activity, and the suggestion has been made that some spatial and temporal patterns of mining would minimize the likelihood of extinction. Terborgh and Winter (1980), in their review of the causes of extinction in better studied systems, point to fragmentation, isolation of one part of a population from others, as a major cause of extinction. Assuming that a mined area does form an appreciable barrier for normal dispersal of at least some populations, the worst mining pattern would thus be one that would cut a more or less continuous, wide swath through the deep-sea habitat. Without more autecological information (e.g., on dispersal abilities of deep-sea species), however, the ecologically optimal mining pattern defies prediction.

Detection of Impacts

The specter of extinction of deep-sea populations carries with it its own "Catch 22" insofar as detection is concerned. Despite extensive and intensive sampling at the various DOMES sites (Hecker and Paul, 1979; Jumars and Self, unpublished), the point at which further sampling would yield few additional species has not been reached at any site within the DOMES region. It is precisely those species that have not yet been sampled which would be predicted to be most extinction prone since, "Rarity proves to be the best index of vulnerability" (Terborgh and Winter, 1980, p. 132). These rare species and their changing abundances with time and with mining activity could not be detected without monumental increases in sampling effort.

Nor will reductions even in those populations that have been sampled be easy to detect. The largest practicable, quantitative samples now taken from the deep sea are 50 cm by 50 cm (0.25 m²). Once the samples are retrieved and processed on shipboard, it requires roughly one person-month of microscopic sorting just to separate the animals from residual sediments in a single sample. Assuming (optimistically) a random (i.e., Poisson) distribution of individuals among samples, Figure 3 shows how many samples would be required to give reasonable certainty ($P \geq 0.95$) of detecting the most severe impact possible—complete mortality of the local population. It is virtually certain (Hecker

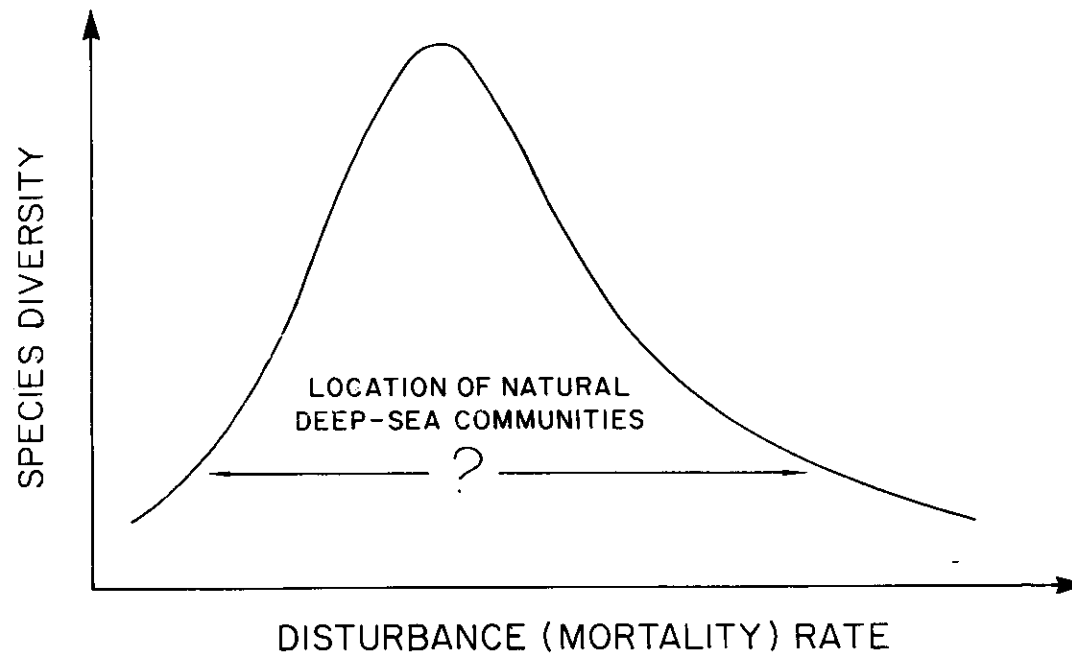


FIGURE 3. The number of 0.25-m² samples required to be reasonably certain of detecting any effect when the population has been decimated entirely (i.e., no individuals are found in any sample) versus natural mean abundance per sample. The χ^2 test of goodness-of-fit to a theoretical Poisson distribution with the specified mean was used to generate the figure, so that the estimates provide reasonable minima (cf. Jumars and Eckman, 1981). Most abyssal populations have mean densities below 0.05 individuals per 0.25-m² sample, making monitoring at the single population level generally impractical.

and Paul, 1979; Jumars and Self, unpublished) that most species in the DOMES region have mean abundances of fewer than 0.05 individuals per sample (< 0.20 individuals per m^2).

With the outlook so bleak for detecting impacts at the single-species level, monitoring will be practical only at the level of guilds or larger groupings, and one might ask what magnitude of impact could be detected for the fauna as a whole (i.e., the best case). Using total observed faunal abundance per sample within a 20-km by 20-km area at DOMES site A and employing the actual variance observed in that parameter (Jumars and Self, unpublished), the question can be answered relatively precisely. With a (manageable) sample size of 20 0.25-m^2 cores, total faunal abundance changes in excess of 50% over the entire sampling region would be necessary to assure ($P \geq 0.95$) detection of the impact, even in this grossest indicator of community condition.

Conclusions

These figures argue against placing great expectations in the results of routine monitoring efforts aimed at evaluating mining impacts. Even relatively large impacts can easily go undetected via traditional before-after comparisons based on random sampling via a surface vessel. This imprecision in sampling estimates is further coupled with the additional imprecision (and potential inaccuracy) of the above predictions; the theories used to make those predictions have not yet been verified in a deep-sea context.

The major reasons behind these problems are easier to identify than are the solutions. First, organisms are extremely sparse, aggravating the already major difficulties in the sheer mechanics of retrieving reliable bottom samples from several kilometers of water. This rarity sets definite limits on sampling precision (cf. Figure 3). Secondly, crucial data are lacking for the DOMES region as well as for other deep-sea areas. For example, generation times, predator-prey relationships, and both qualitative food requirements and feeding rates of deposit and suspension feeders are all but unknown for the animals living on this major fraction of the earth's surface.

No one approach is likely to bring deep-sea ecology quickly to the point where impact predictions can be as accurate and precise as they are in the longer, more thoroughly studied, and more accessible terrestrial ecosystems (e.g., Shugart and West, 1980). However, the most rapid

and sure approach to this sort of knowledge is through iteration between theories and manipulative experiments (Paine, 1977); an accelerated program to couple the collection of essential natural history information with controlled experimentation in an accessible deep-sea environment is sorely needed. Because of the low population densities, high species diversities, and low population growth rates which characterize the deep sea, however, this coupling will not be complete before full-scale manganese nodule mining begins. The obvious challenge, then, is to develop both theories and monitoring schemes which make efficient use of the manipulative experiment provided by manganese nodule mining itself.

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