

# Estimates of direct biological transport of radioactive waste in the deep sea with special reference to organic carbon budgets

Radioactive waste  
Biological transport  
Organic carbon  
Budget  
Flux  
  
Déchet radioactif  
Transport biologique  
Carbone organique  
Bilan  
Flux

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Received 8/7/85, in revised form 21/11/85, accepted 4/12/85,

## ABSTRACT

Calculations can be made for the maximum theoretical transport of pollutants such as radionuclides by movement of organisms out of a deep-sea benthic boundary layer dump site based on a presumption of a steady state organic carbon budget and estimated biological concentration factors. A calculated flux rate depends on the difference between a limiting input of organic matter and that carbon used by the biota or accumulating in the sediment. On average, the potential biological mass transport is low compared to physical transport. Exceptions to this generalization are possible in the far field after spatial gradients are obliterated or if natural mass migrations or periodic spawning concentrations occur in the near field. Biologically mediated fluxes of contaminants due to mixing of sediments by bioturbation or vertical flux due to scavenging by sinking particles are significant for movements of pollutants to and from sediments. These pathways contribute to the direct input of contaminants into food webs which may contain harvestable species. These fluxes are unimportant for mass transfers in the ocean but they determine the exposure of critical groups to contaminants,

*Oceanol. Acta*, 1986, 9, 2, 199-208.

## RÉSUMÉ

Estimations du transport biologique direct de déchets radioactifs dans les fonds marins en relation avec les bilans de carbone organique

Le transport théorique maximal de polluants tels que les radioéléments peut être calculé par le déplacement d'organismes en dehors de la couche limite benthique du site de rejet; le bilan de carbone organique est supposé stationnaire et les valeurs des concentrations biologiques sont estimées. Le flux calculé dépend de la différence entre l'apport limitant de matière organique et la quantité de carbone utilisé par le biotope ou accumulé dans le sédiment. En moyenne, le transport biologique potentiel est faible comparé au transport physique. Des exceptions peuvent se trouver en dehors de l'aire de rejet lorsque les gradients spatiaux s'effacent ou dans le cas de migrations naturelles, ou encore dans celui des concentrations périodiques de frai.

Les flux biologiques de polluants dus aux mélanges de sédiments par bioturbation ou le flux vertical dû à la sédimentation des particules caractérisent les transports de polluants vers les sédiments ou en provenance de ceux-ci. Ces voies favorisent l'entrée de polluants dans des chaînes alimentaires pouvant contenir des espèces à récolter. Les flux sont négligeables dans les transports de masse dans l'océan, mais ils conditionnent l'exposition aux polluants de certains groupes critiques,

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## INTRODUCTION

The biological consequences of disposing of radioactive wastes in the deep ocean are considered to be poorly known (Anon., 1971; Rice, 1978; Gomez, 1980). So few data are available that discussions of the subject conceptualize problems only in general qualitative terms (Yayanos, Nevenzel, 1978). The present paper improves this by using newly-acquired information on the flow of energy in deep ecosystems to estimate the maximum potential export by biological processes.

This newly-acquired ability to budget the energy and carbon fluxes in deep-sea ecosystems has implications beyond the biology of the organisms involved. It allows speculation for the first time on the degree of interdependent coupling between the surface ocean and great depths (Eppley, Peterson, 1979). Pollutants can be transferred either in or out of isolation in the deep sea along pathways that are part of and may be proportional to this interdependent coupling.

The deep-sea dumping of radioactive wastes is now controlled by limitations defined by the London Dumping Convention (LDC), based on recommendations from the International Atomic Energy Agency (IAEA). Although uncertainties in calculations of the transport of radionuclides by all possible mechanisms from a deep dump site to man cannot be estimated, growth in our knowledge of oceanic processes is so rapid that the IAEA has agreed to bring their recommendations to the LDC up to date periodically. With this in mind, the IAEA and the LDC asked the Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) of the United Nations to form an *ad hoc* working group that would contribute to this task. The group produced a report (GESAMP, 1983), which is a state-of-the-art review of the physical oceanographic processes relevant to deep-sea contaminant dispersion. A number of conclusions concerning the potential biological involvement in these processes were presented (*see* Executive Summary, GESAMP, 1983) and these are the subject of this paper.

## RESULTS AND DISCUSSION

### Mass transport by organisms

One conclusion of the Executive Summary (GESAMP, 1983) is concerned with the mass transport of a contaminant that would be large enough to alter a concentration field otherwise established by a combination of physical and geochemical processes. It involves gross quantities of matter introduced at a dumpsite. On the other hand, while a significant "exposure pathway" may be created by a foodchain, such a transport need not have a discernible effect on the overall pattern of distribution. The Executive Summary conclusions and our analysis in this paper deal with the question of mass transfer by biological processes and how they compare with competing physical dispersion processes. There are several situations under which biological processes are responsible for greater mass transport than are physical processes. Among these are: 1) the

indirect effects due to bioturbation, or the mixing of surficial sediments and exchange of pore water by the activity of animals; and 2) the direct transport of, or concentration in, animals or plants after a sufficiently long period of time that the transport by physical dispersive processes and decay have reached a steady state. The latter biological process will then function to redistribute a pollutant in a manner proportional to biomass and concentration factors. It is this reconcentration in the far field where spatial gradients are very slight that the biological redistribution could be important in mass transfer as well as in foodchains leading to man. Bioturbation is very important in accelerating the binding of ions and then moving the bound ions taken out of solution from the sediment interface to depth within the sediments. Continuous exposure of subsurface particles reworked to the sediment surface may promote scavenging. None of these processes will be considered in this paper, which deals exclusively with the direct transfer of material by organism movement.

### Water mass and biomass transport in the interior

The focus here is to estimate the transport and fate of a contaminant from a source on the sea floor, irrespective of "hazards" to the environment or biota, to the points where it could potentially enter man's foodchain. Mass transfer away from the site of entry could be by competing biological and physical processes that would be both vertical and horizontal. The physical processes would be advective, by currents, and by a combination of different mixing processes that on average could be modeled as anisotropic Fickian diffusion. In general, physical processes disperse while biological processes concentrate materials. The biological processes would compete with physical processes through: 1) transfer along foodchains; or 2) migrations. While estimates of the physical processes can be made on a variety of time and space scales, no quantitative information exists on the horizontal and vertical migrations of organisms that would occupy a dump site. We can still calculate the magnitude of biological transport for comparison with dispersion by advection and eddy diffusion.

One useful comparison that can be made is the difference in the mass of water versus the mass of organisms. A mixed bottom boundary layer 50 m thick would contain  $ca. 5 \times 10^7$  g water per  $m^2$ , whereas the biota would weigh at most  $10 \text{ g/m}^{-2}$  at depths where dumpsites would be allowed ( $>ca. 4 \text{ km}$ ; Tab. 1). The total biota (10 g) would have to concentrate a pollutant by a factor of  $10^7$  to carry a concentration equivalent to that in the water mass in which it resides. This suggests that with concentration factors lower than  $10^7$  a larger amount of pollutant will be found in water than in organisms.

Another consideration is the potential transportation capacity of a population of large mobile organisms. Assume an abyssal fish accumulates a contaminant and transports it by swimming. An example of swimming speed would be that of *Antimora rostrata*, chased at  $ca. 40 \text{ cm s}^{-1}$  by DSRV Alvin (Cohen, 1977). In the northwest Atlantic where past dumping was practiced, the fish standing stock is on the order  $0.2 \text{ g m}^{-2}$  (Hae-drich, Rowe, 1977; Polloni *et al.*, 1979). The product

of mass, velocity and a concentration factor (c.f.) gives transport as

$0.2 \text{ g m}^{-2}$  (50 m boundary layer)

$\times 0.4 \text{ m} \cdot \text{s}^{-1} \times \text{c.f.}$

$= 0.08 \text{ g} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \times \text{c.f.}$

This compares to  $5 \times 10^7 \text{ g}$  water (from above) that moves at average velocities of  $20.0 \text{ cm s}^{-1}$  ( $0.2 \text{ m s}^{-1}$ ), although much greater velocities are possible:

$5 \times 10^7 \text{ g m}^{-2}$  (in the BBL 50 m)

$\times 0.2 \text{ m s}^{-1} = 1.0 \times 10^7 \text{ g m}^{-2} \text{ s}^{-1}$

or a ratio of  $(1 \times 10^7)/0.08 = \sim 10^8$ . That is, the concentration factor in the fish would have to be  $10^8$  to be equal to the potential transport in the water mass. A comparison using hypothetical values of  $0.3 \text{ g fish m}^{-2}$ , 10 m of bottom boundary water column above the seabed and velocities of  $1 \text{ cm s}^{-1}$  for water versus  $1 \text{ m s}^{-1}$  for the fish, leads to the conclusion that the concentration factor must exceed  $3 \times 10^5$  for transport by the fish to equal that of the water (GESAMP, 1983).

The above scenario is a hypothetical one-time-only unidirectional event in which a broad range of values could be used. Although we know that some fish congregate in schools and swim long distances (tuna, salmon), mass migration of the total benthopelagic fish fauna (the  $0.2\text{-}0.3 \text{ g m}^{-2}$ ) is not an occurrence that has ever been documented. For theoretical reasons outlined below, it should not occur.

#### Theoretical potential exchanges based on steady state carbon budgets

New data on deep ocean mass or energy flow budgets can be used to provide another approximation of possible biomass production and export limits. A simplified representation of a benthic boundary layer system (Fig. 1) shows that the input of particulate organic

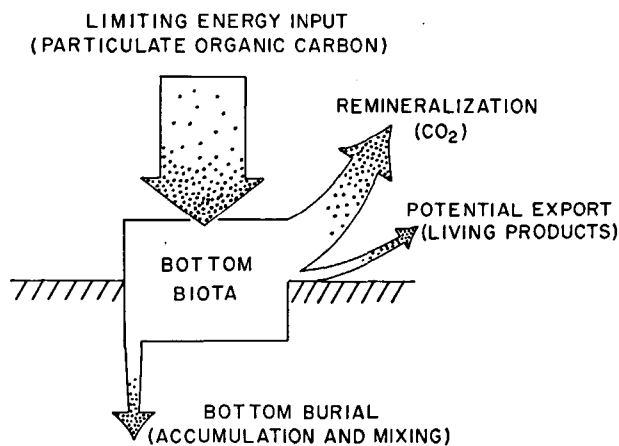


Figure 2

Rates of flux of particulate organic matter to the deep sea versus depth in the ocean. See Table 2 for sources.

carbon (POC) to the seabed has two fates: burial or biological consumption. The biological utilization can be divided into consumption by the various groups of organisms at rates proportional both to their individual and collective biomass, represented by first-order linear functions. As a general rule, for slow growing or mature invertebrate and vertebrate fauna, the major fraction of biologically assimilated energy ( $\sim 90\%$ ) will be used in respiratory conversion to  $\text{CO}_2$  and not new organic matter or production (Rowe, Deming, in press). The remaining  $10\%$  goes to production and will be consumed by a higher trophic level or be exported if the standing stocks are in steady state. In other words, unless the ecosystem is energetically imbalanced or not in steady state, only this  $10\%$  can be transported. One exception to this is the recognized ability for small-size organisms (bacteria, meiofauna) to grow rapidly. Their small size allows a rapid response to conditions favorable for growth (such as increased food supply). In these cases, much more energy, both in absolute terms and relative to respiration, can be directed towards increases in biomass (growth). The details of trophic interactions between various size groups of benthic organisms are poorly known, but rearrangement of terms demonstrates that input of mass or energy less accumulation in the sediment and respiration equals the total export of mass or organically fixed energy.

Export = Input

$$- \text{Respiration} - \text{Accumulation} \quad (1)$$

The input term or flow of energy (sinking particulate organic carbon, POC) that maintains life in the deep sea has been measured using particle traps moored in both the Atlantic and Pacific Oceans at all but the greatest depths (Fig. 2). These POC measurements include the 4 to 6 km depth range that encompasses present or potential deep ocean dump sites. This flux or the input term of the budget varies from several grams carbon  $\text{m}^{-2} \text{ y}^{-1}$  on the upper continental rise to less than  $0.5 \text{ g carbon m}^{-2} \text{ y}^{-1}$  on deep abyssal plains (Tab. 2, Fig. 2). A small portion of this annual supply (Müller and Suess, 1979) is buried as the sediment accumulates. The remainder (Fig. 3) is utilized by bacteria, meiofauna, and macrofauna (all box 2) that

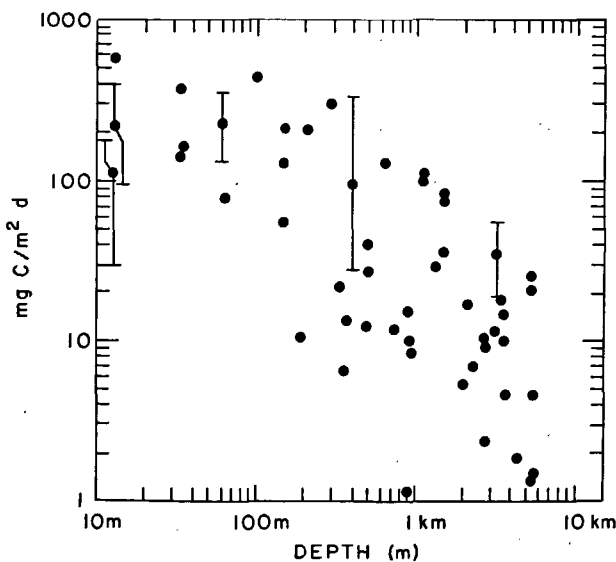


Figure 1

Conceptualized flow of energy or matter into (POC) and out ( $\text{CO}_2$ , production) of the biota of the benthic boundary layer. Living exports are the theoretical carriers of radionuclides out of the system, potentially to man.

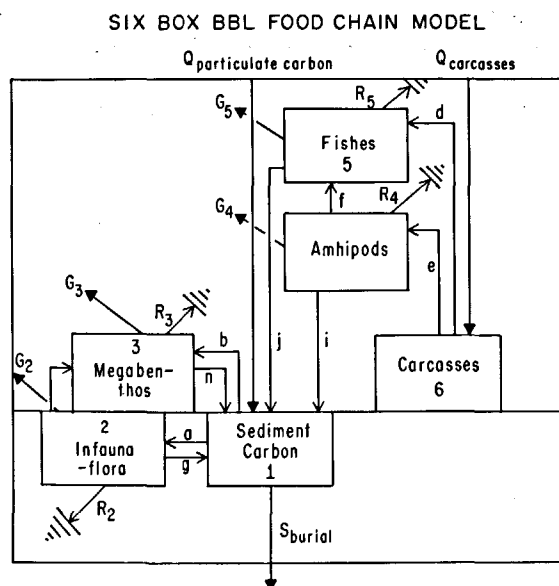


Figure 3

Flow diagram of the inputs and fates of organic matter to the deep sea. Conceptual model of principal biological components of a benthic boundary layer system, with arrows (a-j) representing flows of organic matter and energy. Inputs ( $Q$ 's) are the source of energy or organic matter, while losses are due to burial ( $S$ ), export of gonads ( $G$ 's), and respiration ( $R$ 's). Migration and predation are possible but not explicitly featured in the diagram. Appropriate data on many variables and fluxes in Tables 1-3.

live in or on the sediment, and by benthic and benthopelagic fishes and invertebrates (boxes 5 and 6), which live on and above the sediment. A group of scavengers completes the food-web, but it is not known how much of their diet consists of carcasses ( $Q_c$ ) or the organisms that consume the small detrital particles ( $Q_p$ ) raining slowly to the sea floor. The ranges in stock sizes of the state variables in Figure 3 are given in Table 1, while the fluxes on which some information exists are given in Table 2.

The classification of organism groups according to size allows some conclusions about food-chain relationships. For example, the maximum transfer of mass through or out of the system can be calculated. Knowledge of reproduction and development ( $G_2$ - $G_5$ ) allows assumptions to be made on what groups will

Table 1

Estimates of wet weight biomass ( $g\ m^{-2}$ ) for various size groups of benthic organisms in sediment (to a few cm depth) or just above the bottom at abyssal depths  $>4000\ m$ . Data are from Atlantic and Pacific sites which vary in levels of primary production. 1 g carbon is assumed to be contained in 24 g wet weight for all organisms except bacteria.

Group	Biomass ( $g\ m^{-2}$ )	Carbon equivalent ( $mg\ carbon\ m^{-2}$ )	Reference
Bacteria	~0.2-2.1	20-210	Watson <i>et al.</i> , 1977; Williams and Carlucci, 1976; Rowe and Deming, 1985.
Meiofauna ( $>40\ \mu m$ )	0.05-0.5	2-20	Thiel, 1983; Sibuet <i>et al.</i> , 1984; Tietjen, 1984; Snider, Burnett and Hessler, 1984.
Macrofauna ( $>250\ \mu m$ excl. foraminifera)	0.01-10.0	4-400	Rowe, 1983
Megafauna (epifauna) ( $>1\ cm$ )	0.02-1.0	0.8-40	Haedrich and Rowe, 1978; Haedrich <i>et al.</i> , 1980; Carney and Carey, 1976.
Scavenging amphipods	0.01-0.1 (?)	0.4-4	Ingram and Hessler, 1983; Rowe, Sibuet and Vangriesheim, in press.
Fish (benthic and benthopelagic) (abyssopelagic integral 4000-5000 m)	0.02-1 (?)	1-40	Pearcy, Stein and Carney, 1982; Cohen and Pawson, 1977; Haedrich and Rowe, 1978; Haedrich <i>et al.</i> , 1980; Merrett (unpubl. data); Angel and Baker, 1982
Abyssopelagic plankton (macrozooplankton) near the sea bed = integral biomass 50 m above bottom	0.01-0.12	0.4-5	Wishner 1980

export eggs, larvae, or juveniles out of the system. Mature stages may migrate to spawn, for example, which would constitute a "system reproductive export".

As mentioned above, in larger sized organisms, energy intake is used primarily for respiration, with all production exported to maintain steady state. The calculations assume that bacterial production is consumed by meiofauna and macrofauna. Megafauna (box 3), which include roaming and sessile large invertebrates on the sediment surface, are consumers of all three groups of smaller organisms. Some are known to have reproductive stages that would be exported ( $G_3$ ). Using respiration data of Smith (1978) and biomass data from Haedrich and Rowe (1977), Rowe (1981) concluded that the total carbon assimilation of the larger organisms relative to the smaller ones was small, but this needs further evaluation when more data become available.

This steady state budget (equation 1) can be used to calculate potential transport in the western North Atlantic, based on data from the Continental Shelf to the Hatteras Abyssal Plain (Smith, 1978; Rowe, Gardner, 1979; Honjo, 1978; 1980; Hinga *et al.*, 1979; Rowe, 1981). The POC flux, burial and respiration (Rowe, 1981) at the depth of a dumpsite (defined by the London Dumping Convention) can be estimated, solving for the potential export:

Export = Input - Burial - Respiration.

$$= 0.5\ gC\ m^{-2}\ y^{-1}. \quad (1a)$$

This calculation indicates that at most 0.5 g carbon  $m^{-2}\ y^{-1}$  [ $\times 24$  (Tab. 1) = 12 g fresh weight  $m^{-2}\ y^{-1}$ ] is available for export by living organisms.

Table 2

Fluxes of organic carbon in the deep sea ( $g\ cm^{-2}\ y^{-1}$ ).

Input	Burial	Respiration
0.5-3.0 <sup>1</sup>	0.02-0.9 <sup>2</sup>	0.02-0.5 <sup>3</sup>

<sup>1</sup> Suess, 1980; Honjo, 1978, 1980; Rowe and Gardner 1979; Hinga *et al.*, 1979; Deuser *et al.*, 1981; Sibuet *et al.*, 1984; Rowe and Deming, 1985 (See Fig. 2).

<sup>2</sup> Müller and Suess, 1979; Sibuet, *et al.*, 1984; Rowe and Deming, 1985; Mauviel, *et al.*, 1982.

<sup>3</sup> Smith, 1978 a, b; Hinga *et al.*, 1979; Smith and Hinga, 1983

It should be stressed, however, that the range of values for the three known variables (input, burial and respiration) is very great (Tab. 2). Note, for example, that the sum of the maximum values of burial and respiration is greater than the minimum estimated input. Considerable research needs to continue to determine the source of the variation for specific sites. It is already apparent that the primary particle flux varies seasonally (Deuser *et al.*, 1981). Although a large fraction of assimilated food may be respired leaving a small fraction for potential export, radionuclides are not respired and may accumulate (or not) in older organisms.

#### Comparison of average theoretical biological transport and average physical transport

An important comparison is between the maximum theoretical biological transport and physical transport processes (Robinson, Mullin, 1981). Vertical biological transport is biomass production ( $P$  = "Export" above) transported to the surface characterized by a concentration factor, c.f., for a contaminant. This may be compared with the net physical transport by a typical average upwelling velocity of  $w = 10^{-5} \text{ cm s}^{-1}$  or  $3 \text{ my}^{-1}$ . One obtains:

$$\frac{\text{contaminant transfer by biological production}}{\text{average contaminant transfer by physical upwelling}} = \frac{\text{c.f.} \times 12 \text{ gm}^{-2} \text{ y}^{-1}}{3 \text{ my}^{-1} \times 16^6 \text{ gm}^{-3}} = 4 \times 10^{-6} \text{ c.f.}$$

Thus, even for a relatively large concentration factor (c.f. =  $10^3$  to  $10^4$ ; Jackson *et al.*, 1983), the average vertical biological transport based on this steady-state carbon budget will be small compared to the physical transport.

Although this analysis again implies that the effect of physical transport on the concentration fields of a contaminant is more important than potential transport by organisms, it applies only to yearly and basin-wide averages. Concentration of the biological transport in small space or time scales could increase biological importance, as discussed below.

#### Release of reproduction products

Localized concentrations of organisms might increase their potential as transport vectors. Suppose that an organism within a geographic distribution of several hundreds of kilometers aggregates periodically to spawn. An example is the eel, *Synphobranchus kaupi*, which is abundant in slope waters around the North Atlantic Ocean, and spawns in the Sargasso Sea region (Bruun, 1937). If spawning aggregation occurs in the presence of maximum concentrations of contaminants, e.g., around the dump site, and if the maximum concentrations in reproductive products is reached quickly, then the release of buoyant eggs might provide an accentuated contaminant transfer mechanism. The steady-state, average-carbon-budget limitations do not apply because the spawning organisms are drawing on the carbon supplied to an area far larger than the one in which they are spawning. A similar argument can

be made for spawning on a short time scale. The carbon could be accumulated over a long period, even up to multiple years, and released over a few short weeks, wherein the biological rate during this pulse would be far greater than the average value.

If the species in question spawns  $1/4$  of its body weight and has an average biomass of  $1 \text{ gm}^{-2}$  over an area of  $10^6 \text{ km}^2$ , then the production ( $P$ ) of buoyant eggs could be  $2.5 \times 10^{11} \text{ gy}^{-1}$ . The average maximum concentration of the contaminant in the dump site area for a diffusive ocean can be given by

$$C_{\text{max}} = \frac{Q}{\pi (K_V K_H)^{1/2} r_s}, \quad (2)$$

where  $r_s$  is the radius of a distributed source (the dump site) area.  $K_V$  and  $K_H$  are vertical and horizontal effective dispersion coefficients and  $Q$  is the source's release rate. If the area of spawning is greater than the dump site, the appropriate average concentration can be obtained within a factor of 2 by replacing  $r_s$  by the radius over which spawning takes place.

The total flux ( $F_s$ ) of the contaminant to the surface by buoyant eggs can be given by:

$$F_s = \text{c.f.} \times P \times C_{\text{max}} \times \rho_B^{-1}, \quad (3)$$

where  $\rho_B$  is the density of the eggs, c.f. is the concentration factor,  $P$  is the production rate, and  $C_{\text{max}}$  is the concentration of contaminant in the dump site. The flux carried by such eggs (when averaged over the area in which the fish spawn) will be small for long-lived contaminants averaged over a year compared to that due to physical processes, for the reasons given above.

The flux (3) constitutes a source to the surface water, but once at the surface this will be dispersed, as was the bottom source, according to (2). The resulting maximum surface concentration would then be

$$C_s = \frac{F_s}{\pi (K_V K_H)^{1/2} r_s} = \frac{\text{c.f.} Q P}{\rho_B \pi^2 K_V K_H r_s^2}, \quad (4)$$

assuming the surface and bottom diffusivities are equal. For contaminants whose decay is small over the time for the eggs to float to the surface, one can compare (4) with the concentration  $C = Q(\lambda V)^{-1}$  for the average concentration at an appreciable distance from the source (the far-field). The ratio,  $A$ , of the surface maximum ( $C_s$ ) to the far field ( $C$ ) would be

$$A = \frac{\text{c.f.} \lambda P V}{\rho_B \pi^2 K_V K_H r_s^2}. \quad (5)$$

Taking  $P$  as above,  $V = 10^{17} \text{ m}^3$ ,  $K_V = 10^{-4} \text{ m}^2 \text{ s}^{-1}$ ,  $K_H = 10^2 \text{ m}^2 \text{ s}^{-1}$ ,  $\rho_B \approx 1$  and the area of the dump site to be  $10^4 \text{ km}^2$ , then

$$A = 3 \times \lambda \times \text{c.f.} \times 10^{-6}, \quad (6)$$

where the units of  $\lambda$  are  $\text{s}^{-1}$ . In this case, for a long-lived element such as plutonium ( $\lambda \approx 9 \times 10^{-13} \text{ s}^{-1}$ ),  $A$  is small as long as the concentration factor is less than  $10^5$ .

There are several situations, however, where the ratio of the surface maximum resulting from such a biological

migration might be significant. For short-lived elements the concentration resulting from buoyant eggs could be significant in comparison to that resulting from physical processes, since a short transit time for the eggs to the surface would allow some of the contaminant to reach the surface before decay. The calculation above (A) compares a continuous yearly average and if the release of buoyant products occurs over a short time period of a few weeks to months then the ratio would vary over the year. Periodic reproduction is known to occur in some deep-sea species (Tyler, Gage, 1980; 1983; 1984; Tyler *et al.*, 1982; Gordon, 1979).

Another important variable is the size of the area of spawning. Reducing the spawning area affects the denominator,  $C_p$ , by the square of the radius  $r^2$ . The exceptions to the average flux based on the carbon budget will occur *only* when the dumpsite and the spawning area overlap. The importance of the biological fluxes will be intensified temporally during spawning, but when averaged over time will have to be constrained in terms of a carbon budget.

### Foodchain amplification

Some pollutants are more concentrated in predators than in their prey. That is, an initial low concentration in prey derived by uptake from water or sediment is increased to a higher level in their predators. The concentration factor of the first level is calculated by a comparison with the environment, whereas the second level in the foodchain could be calculated by a comparison to the first level or to the environment, as well. If the concentration factor for the first level is  $10^3$ , and the concentration factor for the secondary consumer or predator is  $10^3$  compared to the initial organism, then the overall c.f. for the second group would be  $10^6$ . At the same time, the amount of mass produced by the second group would be on the order of 0.1 of the original group, or the pollutant in question would be found in 1000 times greater concentration in a mass of organisms that is 1/10 the original mass, this being an oversimplified example.

Complex foodchains of several levels might be hypothesized to transport material out of dumpsites by concentrating a pollutant up foodchains from those organisms that are not now utilized as a fisheries resource to organisms at shallower depths that are so utilized. While concentration factors on phytoplankton and in metazoans vary over several orders of magnitude among different metals, no evidence has been found in fisheries in the Irish Sea that radionuclides increase in concentration up foodchains (Pentreath, 1980). We do not know that deep-sea communities differ from those in shallow water in the ways they transfer radionuclides, and there is presently no reason to believe that they would be different. Food-limited conditions in the deep sea, however, may have led to the evolution of communities of organisms that are remarkably efficient in locating and utilizing food supplies. The tightly linked food webs in abyssal areas, where pools of organic matter in organisms are rapidly exchanged, could function at higher transfer efficiencies than in shallow water. We do not presently know how these

differences, if they occur, affect transfers of elements within a food web.

### Fertilization effects

Standing stock and biomass of the deep-sea fauna decrease exponentially with depth. It is presumed that this is caused by limited food supplies as explained in the carbon budget calculations above (Fig. 2). If a carcass of a dead fish is put on the sea floor, scavengers accumulate around it and consume it very quickly (Isaacs, Schwartzlose, 1975) in a manner common to fishes in most environments. If wood is introduced it rapidly becomes infested with boring molluscs (Turner, 1973). The waste matter from such borers supports a detritus-eating community in close proximity to the wood as well (Turner, 1977). Such observations suggest that the introduction of organic matter into the deep sea could significantly increase standing stocks locally. Experiments to test the rate of succession of deep-sea communities and how they respond to such alien inputs are inconclusive so far, but attention should be paid to some situations where the biological transport processes could be altered by the introduction of alien organic supplies. By increasing the organic input (Fig. 1), the potential export of contaminated products by organisms would be increased. Contaminated soils can contain many different components, including many kinds of organic detritus and flora, including trees, shrubs, *etc.* Placing such materials in dump sites could alter species diversity and abundance of organisms. Attention should be paid to how non-radioactive waste components will alter biological pathways. Organic wastes which could include experimental animals, and other laboratory materials, may need segregation from other materials whose entrance into a foodchain ought to be minimized.

### The artificial reef effect

A possible consequence of deep-sea dumping is the creation of an artificial reef effect. Structures placed on the bottom on shallow, flat continental shelves improve fishing by attracting mobile carnivores and scavengers, by serving as protective refuge for a variety of species. If this "attraction" occurs at deep-sea dump sites, it could increase the potential biological accumulation of a substance by increasing total biomass exposed to radionuclide release. The presumptions about the rates of deep-sea biological transfer may not be applicable in such cases. Total biomass might increase and species composition could be changed to a fauna composed primarily of sessile species living on the waste canisters. How this occurs will depend on the environment at the location and the physical configuration of the waste containers (barrels, submarine hulls, *etc.*). This will put organisms in direct, close contact with substances being released.

When reefs are constructed in shallow water to improve fishing it is questionable whether or not they actually increase total productivity from photosynthesis up through the food-chain associated with the structure. They could be just concentrating fish. The argument

that total production increases is usually based on the effect that the added structure has on currents and turbulence. Mixing is increased, as is hard surface area, and both contribute to higher planktonic and attached algal production.

In the deep sea where no photosynthesis is possible, there seems to be no possibility that higher total production will occur unless altered flow fields accentuate deposition of organic detritus. Attached filter feeders can survive in the deep sea where predictable currents and hard substrates are available. These include principally hydroids, bryozoans, stalked barnacles, glass sponges and crinoids. Few if any are ever encountered on deep-sea moorings. These, as well as mobile animals such as brittle stars, starfish and urchins, would be expected to be attracted to a dump, as organisms are attracted to a shallow-water artificial reef. Carnivorous and scavenging fishes, in this case the rattails, ophidiids, rays, etc., could possibly be attracted to the increased food supply.

How much a dumpsite such as this will contribute to biological concentration and to transfer of substances will depend on the degree to which the dump differs in biomass and production from the surrounding deep-sea. Most bottom water is low in suspended particulate organic matter, with concentrations on the order of 5-50  $\mu\text{g}$  carbon  $\text{L}^{-1}$  (Menzel, 1967; Gordon, 1971). Total suspended matter often increases just above the bottom due to resuspension, but the organic matter in this is low, reflecting the bottom rather than settling pelagic organic debris. Bottom sediments are depleted in organic matter compared to settling suspended matter (Honjo, 1978; Khripounoff, Rowe, 1985), and therefore it seems unlikely that any concentrating factors related to flow field, erosion and deposition around a structure will increase biomass and production appreciably.

Increases in biomass and production in localized areas as well as a change in species composition at a dumpsite, though unexpected, would be alterations that would suggest that new pathways might have been introduced that would not have been characteristic of predumping site assessment.

A further ramification, because of the short time and space scales involved, is that any physical, geochemical and biological transport models that might be required for the extreme near-field (within the perimeter of the site) would have to evolve as a dump site fills up with debris. Bottom roughness, turbulence, erosion and deposition, and the biota will all change with the addition of more and more material. How these change will primarily depend on waste form and dumping strategies, as well as the potential for change in the environment.

It has been discovered recently that some very localized areas of the deep ocean have high biomass that is wholly independent of surface water production. Hot sea water that emanates from spreading centers in the earth's crust is rich in reduced ions that support chemolithotrophic bacteria. These bacteria may live symbiotically within metazoan tissues or they may serve as food for the community of large invertebrates that

is found around the rich effluents (Karl *et al.*, 1980). Introduction of contaminants into such systems and the export of contaminated biota out of the system will be proportional to its exports of biological products, but presently no such estimates can be made.

#### Calculation of the horizontal area required to support a hypothetical deep-sea fishery

It is useful to estimate the area of the sea floor capable of supporting a fishery of any given magnitude in assessing the impact of a contaminant via a fishery. Again, a carbon budget and the nature of the ecosystem can be used in making such an analysis. The biomass of organisms per unit area in the deep sea is much lower, perhaps by a factor of a thousand, than that on the continental shelves (Rowe, 1983). Although the absolute values of production in the deep sea are not yet known, it is reasonable to assume that these are correspondingly small, especially since measured rates of growth and respiration are much lower than in shallow water (Sullivan, Smith, 1982). Thus, the area of deep-sea floor required to support a fishery will be much greater than that in shallow water.

To place the problem in perspective one can estimate the area required to support a minimum credible fishery, sustaining a yield of only one fish weighing 600 g per day ( $200 \text{ kg y}^{-1}$ ). Such a yield might (allowing for weight lost during filleting, etc.) be consumed by only one enthusiastic consumer (eating  $300 \text{ g d}^{-1}$ ) or a small group of more moderate consumers ( $30 \text{ people} \times 10 \text{ g d}^{-1}$ ). (These would constitute the "critical population" in a traditional risk analysis.) A common rule of thumb in fisheries is that sustainable yield is roughly 25% of the pristine biomass (B) times the natural mortality (M). A value of  $M=0.1/\text{y}$  would be considered low in coastal fisheries, but may be appropriate for the deep sea where turnover rates might be assumed to be lower. The pristine biomass required to sustain the given annual yield would thus be taken to be about 40 times the yield, or 8000 kg.

As noted above, the major source of food for deep-sea communities is presumed to be particulate organic detritus (Fig. 1). The potentially exploitable fishes are not detritivores, but scavengers or predators, so at least one trophic level probably exists between the organic detrital supply and such a fish population (Fig. 3). An assumption (based on shallow water fishes *e.g.* cod, *Gadus morhua* (Daan, 1973)) that the fish population consumes about 1% of its weight per day implies a consumption of 80 kg/d. Taking the energy conversion efficiency of the necessary intermediate trophic level to be 10%, the detrital food supply required is 800 kg/d or about 300,000 kg/yr. It was estimated above that of the energy flux to the deep sea (Fig. 2), less than about 20% is utilized by large animals for production, since more than 80% is either respired by organisms in the sediment, in water near the bottom or is accumulated on the bottom in a presumably refractory form. The amount used for production would be no more than  $2.0 \text{ g m}^{-2} \text{ y}^{-1}$  of organic matter (wet weight) or about  $0.1 \text{ g carbon m}^{-2} \text{ y}^{-1}$ . Comparison of this supply with a required  $300,000 \text{ kg y}^{-1}$  ingestion suggests that on

the order of  $1.5 \times 10^8 \text{ m}^2$  is needed to support the hypothetical, limited fishery ( $200 \text{ kg y}^{-1}$ ). This is equivalent to an area of  $\sim 10 \text{ km} \times 10 \text{ km}$ .

Growth rates and respiration rates per unit of biomass are believed to be somewhat lower in the deep sea than in shallow water (Rowe, 1981), and therefore the above extrapolations from shallow water fisheries may be an underestimate. An alternative approach would be to estimate the energy (food) requirements for the population from measures of respiration and total population density. Respiration of the rattail *Coryphaenoides armatus*, using data from the North West Atlantic as an example, is in the order of  $3 \text{ ml O}_2 \text{ kg}^{-1} \text{ h}^{-1}$  (Smith, 1978 *b*). Taking a reasonably high value of  $0.5 \text{ g m}^{-2}$  for the fish biomass at greater than 4000 m depth, respiration would amount to:

$$(3.0 \text{ ml O}_2 \text{ kg}^{-1} \text{ h}^{-1})(0.5 \text{ g m}^{-2}) \\ \approx 13 \text{ ml O}_2 \text{ m}^{-2} \text{ y}^{-1}.$$

This respiration is equivalent to a carbon consumption of  $6 \text{ mg organic carbon m}^{-2} \text{ y}^{-1}$  (Parsons *et al.*, 1984). Production of biomass by deep-sea fish probably lies between 5 and 20 per cent of respiration. Of this one might guess that no more than one-half is available as sustainable yield (although the empirical relationship based on shelf fisheries given above uses one-quarter). Using these production estimates, one obtains the sustainable yield of fish to be 0.15 to  $0.6 \text{ mg carbon m}^{-2} \text{ y}^{-1}$  or  $3.6$  to  $14 \text{ mg m}^{-2} \text{ y}^{-1}$  production of wet weight. Thus, the area required to sustain the hypothetical limited fishery of  $200 \text{ kg y}^{-1}$  could range from  $1.4$ – $5.6 \times 10^7 \text{ m}^2$ , an area slightly less than estimated above.

Both the above estimates rely on assumptions about the nature of potential deep-sea fisheries. The first extrapolates empirical formulae for shallow fisheries to the deep-sea, while the second uses measurements of the respiration and biomass of deep-sea fish but requires hypothetical assumptions to be made regarding the ratios between respiration, production and sustainable yield. None of the steps of the two calculations are, however, inconsistent with what is known of the deep-sea ecosystem. The calculations also are for an equilibrium fishery in a particular location and are not appropriate for estimating the initial yield from a given area or the yield from a moving fishery exploiting virgin stocks.

#### The present weaknesses in the hypothetical carbon-budget constraints

All the above calculations have used recently accrued data on deep-sea ecosystem carbon budgets to indicate

how such budgets can be used to estimate possible constraints on maximum potential export of contaminated biota from deep-sea dumpsites. The implicit assumption in such budgets is that the primary input of energy to the deep ecosystem is in the form of small particulate detritus, POC (Fig. 2), and that this is measured accurately with sediment traps. If the trapping technique underestimates total flux, then the maximum export inferred from use of Figure 1 would be in error by that amount. In areas where the flux is highly seasonal (Billett *et al.*, 1983), traps deployed for short time periods or at an inappropriate time of year could seriously underestimate the flux, perhaps by an order of magnitude. Microbial degradation in the traps or loss due to winnowing from the traps are both strong possibilities for sources of such errors (Gardner *et al.*, 1983; Gardner, 1980; Ducklow *et al.*, 1985).

Another possibility is that input to the bottom is in forms of organic matter that are larger than the POC captured in traps. Scavengers rapidly locate and consume carcasses sent to the bottom in traps or below cameras (Isaacs, Schwartzlose, 1975; Ingram, Hessler, 1982; Hessler *et al.*, 1978; Lampitt *et al.*, 1983; Wilson, Smith, 1984). Unfortunately, the standing stocks of such species are not known, nor is the importance of the input of carcasses compared to that of POC. A summary of fish biomass distribution (Tab. 3) can provide an upper limit to the potential supply of carcasses from fish to abyssal environments. If natural mortality removes 10% of the standing stock annually (assumed above), then  $0.02$  to  $0.06 \text{ g C m}^{-2} \text{ y}^{-1}$  would be available as carcasses (4 to 6% of estimated input of POC; Tab. 2). Carbon budget calculations of potential export will have been significantly underestimated if the importance of this food source is greater than this amount.

Table 3

Comparison of values for fish biomass and production in central gyre regions of the ocean. Recalculated from Mann (1984) assuming that 1 g fresh weight = 1.75 kcal and a wet weight: carbon ratio of 20 since the fish are often lipid rich..

Depth Zone	Biomass	Production
	$\text{g C m}^{-2}$	$\text{g C m}^{-2} \text{ y}^{-1}$
Epipelagic Zone (0-200 m)		
Top Carnivores	$0.8 \times 10^{-3}$	$0.6 \times 10$ – $0.8 \times 10^{-3}$
Forage Fishes	0.01	0.01–0.04
Mesopelagic Zone (200–1000 m)		
Over shelves and Slopes	0.1–0.4	0.01–0.02
Open Ocean	0.05–0.1	0.03–0.05
Bathypelagic (below 1000 m)		
Bathypelagic Species	$0.6 \times 10^{-3}$	$0.06 \times 10^{-4}$
Benthic Species	0.03–0.06	$0.03 \times 10^{-2}$
Total <sup>1</sup>	0.2–0.6	0.05–0.3

<sup>1</sup> Upper and lower estimates calculated by summation using maximum and minimum values.



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