Cornwell JC, Porter ET (2009) Biogeochemical factors, p. 93-101. *In* JE Petersen, VS Kennedy, WC Dennison, WM Kemp. Enclosed Experimental Ecosystems and Scale. Tools for Understanding and Managing Coastal Ecosystems, 222 p., Springer-Verlag, ISBN 978-387-76766-6.

Biogeochemical factors

J.C. Cornwell and E.T. Porter

There are a number of reasons for incorporating sediments in experimental ecosystems

The presence of sediment in mesocosm studies increases the realism of the experiments, in terms of including more biogeochemical cycling processes and more types of organisms (macrophytes or microphytic benthos obviously require a stable substrate; Fig. 112). Three major reasons to incorporate sediments into experimental ecosystems are described below.

Firstly, sediments have large anoxic zones that are required to reproduce natural cycles of nutrients and contaminants, which are highly sensitive to oxidation-reduction (redox) conditions. For example, reducing conditions may promote the loss of water column nitrate by denitrification, the dehalogenation of organic compounds, and the removal of trace metals by precipitation as sulfides.

Secondly, benthic faunal filter-feeding processes and the reworking of sediment are important to the overall biogeochemistry and ecology of an ecosystem, both in terms of the fate of water column organic matter and the recycling of nutrients and other chemicals.

Thirdly, sediments are almost always the major sink for contaminants, often representing a legacy of prior pollution. In most cases, toxicological experiments relevant to coastal ecosystems require sediments.

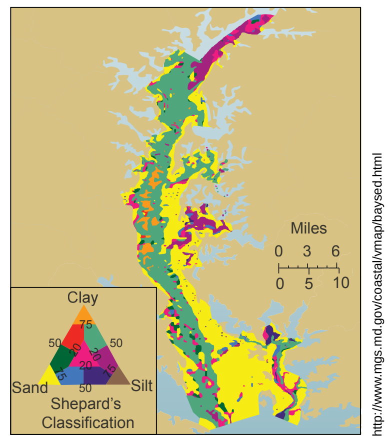


Figure 113: *Distribution of sediment grain sizes in Maryland's portion of Chesapeake Bay.*[89]

Within a single aquatic system, the size distribution of particles in the bottom sediment can be quite variable, as shown for Chesapeake Bay (Fig. 113).

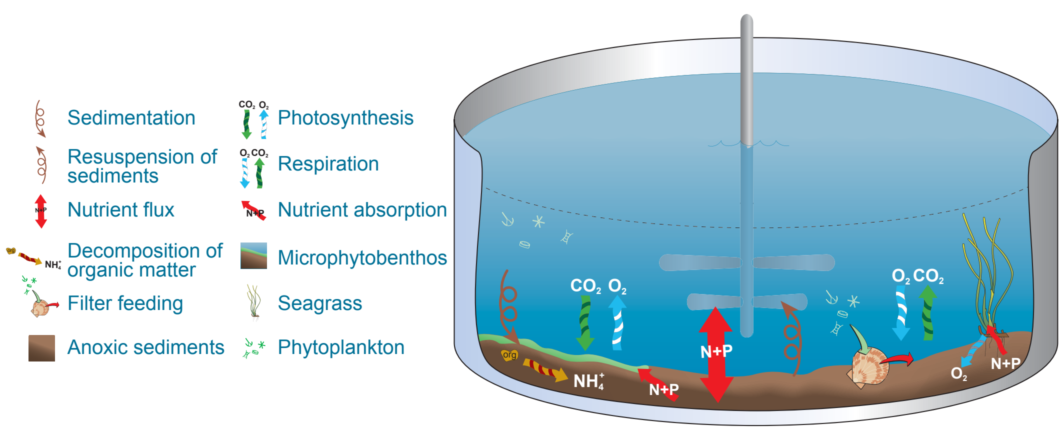


Figure 112: *Experimental ecosystems with sediment can simulate biogeochemical processes found in nature.*

89. Adapted from Kerhin et al. 1988

The first step in designing mesocosms with sediments is to consider the relative benefits of several variables

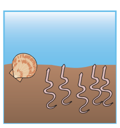
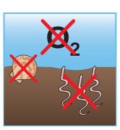
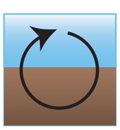
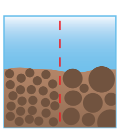
The nature of sediments required for mesocosm experiments may vary depending on the research questions to be addressed. Sediments may require a particular grain size distribution, or they may need to be subjected to different mixing regimes. For some experiments, resident infauna may need to removed. There are advantages and disadvantages to these actions (Table 11).

The choice of grain size can have effects on sediment resuspension, advection of water through sediment, adsorption/desorption of chemicals, sediment redox, and the suitability for specific benthic organisms. Increasingly, scientists are aware that water, solute, and sometimes fine particulates can flow through sediments of coarser grain size.

The fundamental mineral composition of the system can be variable and this may change both the physical and the chemical structure of the sediments. For experiments involving tropical or subtropical environments, a carbonate type of sediment is generally required. If an experimental system is to simulate deep, anaerobic, estuarine environments (like Chesapeake Bay), it needs a sediment with fine grain size. For high-energy shallow water and beach environments, coarser grained sediments would be generally required.

One should also consider the presence or absence of contaminants in the sediments, as well as marine and freshwater minerals (e.g., pyrite, calcite). In addition, the suitability of temperature, redox, and salinity regimes must be considered in relation to microbial communities. Also, pre-existing labile organic matter can have a profound effect on oxygen and nutrient dynamics during the course of the experiment.

Table 11: *Relative benefits of different sediment mixing regimes, grain size, and maintaining or removing infauna.*

	Sediment treatment choice or grain size	**Advantages**	**Disadvantages**
	No treatment, intact cores	Less disruption of microbes, animals, plants, biogeochemical gradients	Inability to prescribe biological community; difficulty in collection and emplacement in large mesocosms
	Defaunation by oxygen depletion	Can prescribe animal species and density	Mild disruption of sediment biogeochemical structure
	Sieving, homogenization	If desired, decreased sediment heterogeneity can prescribe animal species and density	Severe disruption of sediment biogeochemical structure
	Grain size choice or modification	Can use coarser sediments to dilute sediment activity, choose sediment metabolic rates	Mixing fine-grained and coarse sediments can result in heterogeneity after emplacement

Particle grain size is a key influence on biogeochemical processes

Coarse-grain sediment particles tend to have strong resistance to resuspension as well as higher settling velocities. In lacustrine and estuarine physical regimes, resuspension is generally more important for unconsolidated clay and silt particles, although sand may also be transported in very high energy environments or in episodic storm events.

The resistance to advection (flow) of water and particulates through sediments decreases with increasing grain size. In coarse-grained sediments, there is the opportunity for solutes and particles to be moved rapidly into and through the sediments (Fig. 114), depending on physical forcing. Most devices used for sediment incubations do not simulate this process. Small amounts of fine-grained sediment can minimize this advection by filling in the pore spaces between coarse grain particles.

The grain size of sediments is usually a product of the physical regime such as bottom shear, with fine-grained materials often winnowed out during deposition and sediment reworking. In the upper and middle regions of Chesapeake Bay, the organic content of sediments decreases with increasing proportions of coarse-grained materials. This decrease reflects both the difficulty of organic matter to repose in higher energy environments and the low adsorptive ability of low surface area that characterizes coarse sediments.

Figure 114: *Algal cells in the left microscosm have infiltrated the coarse-grained sediment particles as shown by the clear water column. The smaller grain sizes in the remaining microcosm provide greater resistance to such particle advection into the sediments (all three mesocosms have defined bottom shear velocities).*[90]

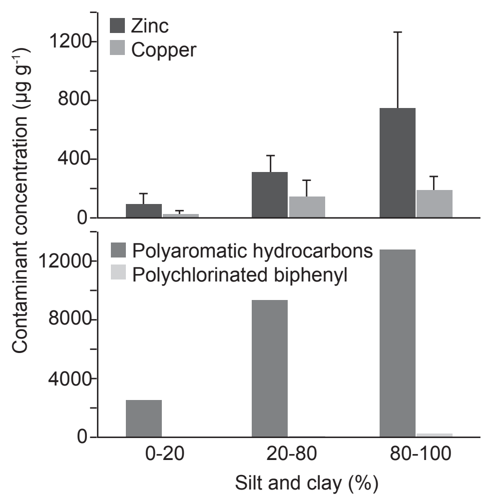


Figure 115: *As the proportion of fine-grained sediment increases (from left to right), the concentration of particle-reactive contaminant species increases.*[91]

Contaminants, including inorganic substances such as metals as well as toxic organic compounds, are generally found at high concentrations in fine-grained sediments (Fig. 115). In the heavily contaminated Baltimore Harbor, for example, the highest contaminant levels are observed in fine-grained sediments. The lower organic matter content of coarser sediments generally leads to lower rates of organic matter decomposition, nutrient regeneration, and oxygen uptake.

For mesocosm studies, the choice of grain size can thus have an effect on the experimental outcome. The initial metabolic rate usually is higher in fine-grained sediments, and such sediments can be an unexpected source of nutrients and an unexpected sink for oxygen. The fate of contaminants added to mesocosms may well be affected by sediment grain size, with generally higher sequestration or adsorption of metals and organics in muds than in sands. However, in MEERC STORM contaminated sediments were added direclty to mesocosms and the effect of tidal and episodic resuspension was studied.

90. Huettel and Rusch 2000, 91. Baker et al. 1997

Metabolic rates of intact sediments vary seasonally at the same site

Although grain size is an important factor, other controlling factors include location within the ecosystem and time of year. Considerations include the following:

- At a given site, there are strong temporal changes in sediment biogeochemistry driven by temperature, changing inputs of organic matter, and changing activity of biota, both animals and plants (Fig. 116).
- In an estuarine setting, the salinity regime of the sediment collection area must be matched with the salinity regime of the influent water. Salinity will affect the microbial, macrobenthic, and floral communities, as well as influence the mineral composition of the sediments and particle aggregation.
- Sediments experience broad ranges of organic matter inputs and quality. The most labile organic matter often is the major contributor to overall sediment metabolism. Addition or depletion of labile organic matter can influence the rates of nutrient exchange. In the Chesapeake mid-Bay, depletion of organic matter (largely from particles sinking in spring and summer) results in a late summer decrease in ammonium flux. Depletion of organic matter during experiments can similarly result in changing rates of biogeochemical reactions. This has a strong influence on microbial processes and solute fluxes.

In deciding on the nature of the sediments to be used in mesocosms, it is important to consider the effects of season on the experimental outcome. Under warm conditions, organic matter in the sediment will decompose at higher rates than under cooler conditions. A consequence of this is that metabolic rates may change as organic matter is depleted, particularly if the experimental design does not include new sources of organic matter. Under cooler conditions, the pool of labile organic matter is metabolized more slowly, with a less dramatic change in overall metabolic rate over time. Thus, temperature interacts with experimental trajectory, particularly in long-term experiments. The accumulation of solutes such as ammonium and phosphate in pore water tends to increase with warmer temperature, with implications for nutrient releases from manipulated sediments.

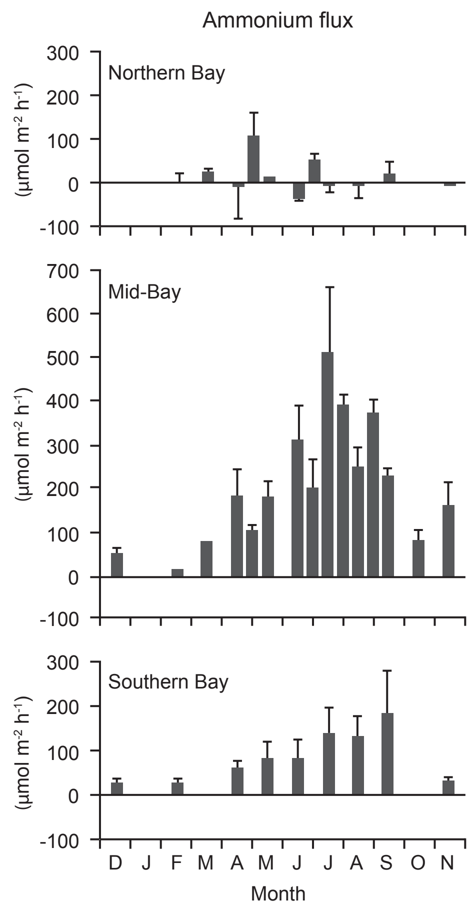


Figure 116: *Average values (mean ± standard deviation) of ammonium fluxes at three stations (Northern Bay, Mid-Bay, Southern Bay) along the main axis of Chesapeake Bay. Data were collected between December 1988 and November 1989. Positive and negative nutrient fluxes represent fluxes out of and into sediments respectively.*[92]

92. Cowan and Boynton 1996

Either intact or homogenized sediments can be used in experimental ecosystems

Photos: Elka Porter

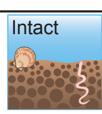
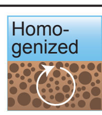
Figure 117: *The various steps in using sediments in mesocosm experiments: a) Mud collection, b) Homogenization (mud stomping), c) Mud smoothing, d) Equilibration.*

In designing experimental systems, choosing to use intact or homogenous sediments (Fig. 117) will produce distinctly different sediment traits but will necessarily involve different logistic constraints. This choice is strongly affected by the research questions being asked (Table 12).

Intact sediments preserve vertical zonation within the sediments. One key zonation is the distribution of labile organic matter. This settles to the surface of the sediment and, in the absence of strong bioturbation, makes the surface sediment regime the most biogeochemically active. Intact sediments also preserve realistic three-dimensional biogenic structures within sediments, including animal tubes and burrows. Preserving the original grain size can be difficult, with physical disturbances during collection, transport, and emplacement potentially resulting in the separation of fine-grained and coarser sediment particles. For most indoor mesocosms such as the MEERC pelagic-benthic systems, the substantial surface area of some mesocosms and the inability to use heavy equipment to transport needed volumes of sediment into the mesocosm room precluded the use of intact sediments.

Grain size can be modified by mixing different proportions of fine-grained and coarse sediments. In preliminary MEERC pelagic-benthic experiments, the initial rate of sediment metabolism had to be minimized to better observe any increases in sediment metabolism and nutrient recycling as a result of organic matter inputs during the experiments. The sediment was constructed from 80% commercial sand with a small amount of fine-grain material from the estuary, using a cement mixer for homogenization. However, when the homogenized sediments were placed in the mesocosms, stirring the water column resulted in substantial movement of the fine-grained sediment, creating pockets of fine-grained material and a very heterogeneous sediment surface.

Table 12: *Advantages and disadvantages of using intact or homogenized sediments in experimental ecosystems.*

Treatment	**Advantages**	**Disadvantages**
 Intact	Realistic animal community Realistic vertical zonation & processes Potential for minimal variability	Difficult and expensive to collect and transport Potential high levels of variability Not possible to specify animal or plant community
 Homo-genized	Easy and less expensive Can specify animal or plant community	Loss of vertical gradients at onset until about 14 days Re-sorting of grain size Disturbed burrow structures

It is important to understand how sediment homogenization affects experiments

The depth of the sediment layer in mesocosms effects the chemistry of an experimental ecosystem. Very shallow sediment layers will not necessarily provide a good mimic of sedimentary conditions in marshes and submerged aquatic grass beds. Depending on the organisms included in pelagic-benthic systems, depth may or may not be important. The most important depths in terms of nutrient cycles and metabolism are near the sediment surface (Fig. 118). Thus, for most mesocosms, it is not necessary to have deep sediment layers to simulate natural metabolic activity.

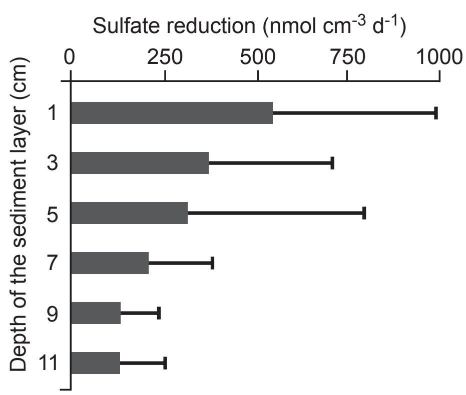


Figure 118: *Annual average vertical profiles of sulfate reduction in mid-Chesapeake Bay. Strongly pulsed organic inputs (algae) result in higher rates of sediment metabolism and very high rates at the sediment surface.*[93]

Chemical changes in homogenized sediments are due to rapid diffusion of elevated levels of ammonium from the sediments.[94] Changes in intact sediments occur more slowly because they are the result of ongoing degradation of organic matter.

Before homogenization, diffusion keeps nutrient concentrations relatively low at the sediment-water interface; homogenization brings high levels of ammonium to the sediment surface and leads to high initial ammonium fluxes (Fig. 119). This effect is not as pronounced for phosphorus because sediment oxidation during homogenization enhances its adsorption to iron oxides.

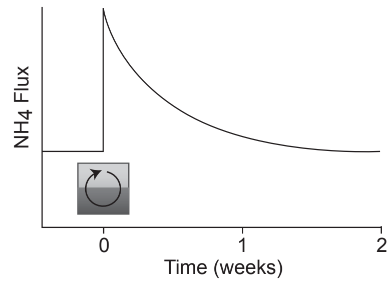


Figure 119: *Initial NH_4^+ flux is high after sediment homogenization, with a return to normal after about two weeks.*[93]

In homogenized sediments, diffusion will decrease the concentration of pore-water ammonium at the sediment-water interface, resulting in a decreased flux of species such as ammonium over time. Prior to homogenization *treatment*, ammonium production and concentration exhibited distinct vertical profiles (Fig. 120, upper panel), which were lost with initial sediment mixing. After *two weeks*, the ambient vertical patterns returned for ammonium concentrate but not production (Fig. 120, bottom panel).

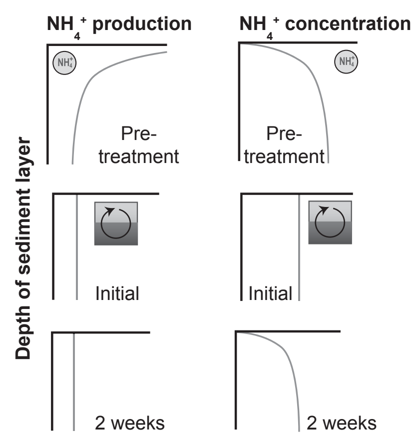


Figure 120: *MEERC's ammonium release experiments showed the pattern idealized (Fig. 119). Pore- water ammonium profiles here are shown at the time of homogenization and two weeks later. The deep sediment had higher initial ammonium than the near-surface sediment.*[95, 96]

93. Marvin-DiPasquale and Capone 1998, 94. Porter et al. 2006, 95. Porter et al. 2004a, 96. Porter et al. 2004b

Sediments can introduce unexpected and unwanted organisms into experimental ecosystems

Sediments do not automatically make experimental mesocosms more realistic. The presence of seeds of aquatic macrophytes and resting stages or cysts of benthic animals in sediments can introduce unwanted organisms (Fig. 121). In some MEERC experiments, the appearance of aquatic grasses and various invertebrates (Fig. 122) was unanticipated. While mechanical filtration of the water column may allow complete removal of pelagic organisms above a particular pore size, and various sieving or sediment preparation procedures can limit the activity of benthic biota, it tends to be very difficult to eliminate sediments as a source of all unwanted organisms if resting stages, cysts, or seeds are very resistant to disturbance.

One possible approach to the question of unexpected biota is to monitor for these species and decide before the experiment whether the experimental protocol includes removal of such biota (if possible).

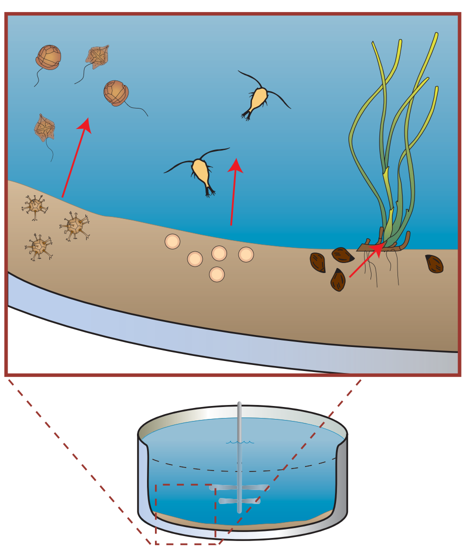


Figure 121: Seeds, resting stages, or cysts of organisms that occur in sediment brought in from nature and not thoroughly defaunated can unexpectedly change the biotic composition of an experimental ecosystem.

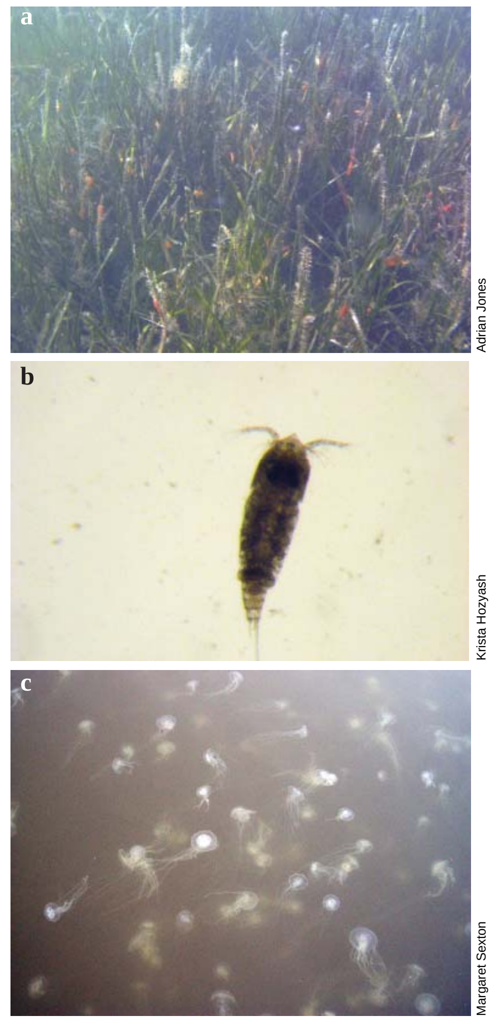


Figure 122: Organisms that can contaminate experiments through introduction of seeds, resting stages, or cysts in the sediment include a) aquatic grasses, b) copepods, and c) jellyfish.

Key sediment measurements are required during experiments

During the course of experiments, the composition and rate of metabolism or nutrient cycling in sediments changes, but the changes occur more slowly than in the water column. The frequency of sampling and the mass or area sampled need to be tailored to the size of the mesocosm, the questions being asked, and potential destruction of experimental habitat.

In addition to container size, research goals may dictate sample amount and frequency. For example, small containers cannot be sampled heavily, especially to provide enough material to measure rates or to allow for replication. Quality assurance and quality control requirements may also dictate the sampling amount and frequency. Table 13 lists the various variables that might be measured in sediments.

Table 13: *Potential variables to be measured in sediments of benthic-pelagic coupling experiments.*

Variable	Utility	Frequency
Particle grain size	Important to adsorption, water flow	1 to 2 times per experiment
Water content/bulk density	Needed for conversion of data between volumetric and mass scales	1 to 2 times per experiment
Solid phase C, N, P	Important for understanding nutrient cycling, organic degradation	1 to 2 times per experiment
pH profile	Used to calculate solute speciation and physical adsorption	Bi-weekly to monthly
Redox profile	Monitors redox transition depth	Bi-weekly to monthly
Pore-water chemistry (O_2, N, Fe, Mn, S, CH_4, P)	Identifies controls on organic decomposition, solute/gas flux, toxicity	Bi-weekly to monthly
Sediment oxygen demand	Measures sediment component of system respiration	Bi-weekly to monthly
Solute/gas exchange across interface (nutrients, metals)	Measures effect of sediments on overlying water	Bi-weekly to monthly
Sediment rate processes (sulfate reduction, methanogenesis, denitrification, N fixation etc.)	Identifies biogeochemical processes and rates within sediments	Bi-weekly to monthly
Algal photosynthesis	Identifies sediment component of system production	Bi-weekly to monthly
Macrofauna	Identifies the effect of fauna on the ecology	Before and after the experiment
Sediment chlorophyll *a*	Measures microphytobenthos biomass	Weekly
Contaminants	isotope tracer studies identify contaminant dynamics	Before and after the experiment

Key water column measurements are required during experiments

Chemical measurements are used to monitor changes during experiments so that environmental conditions can be regulated, to measure the rate of change of a chemical (i.e., nutrient or contaminant appearance or disappearance), or to examine the suitability of a chemical habitat for organisms (i.e., pH, O_2, ammonia, salinity).

The suites of chemical measurements are determined by the goals of the experiment. In toxicology experiments, the response of organisms to added chemicals is of interest, so, to ensure that adding a chemical is causing the response, other chemical constituents should be monitored. Experiments on nutrient cycling and the effects of nutrients on plant and animal biomass or productivity or the effect of animals and plants on the ecosystem may have different time courses of change in both chemical and biological constituents (Fig. 123). Thus, chemical measurements may be required at different sampling intervals, depending on the process being monitored (Table 14) and sediment resuspension is incorporated into mescocm experiments.

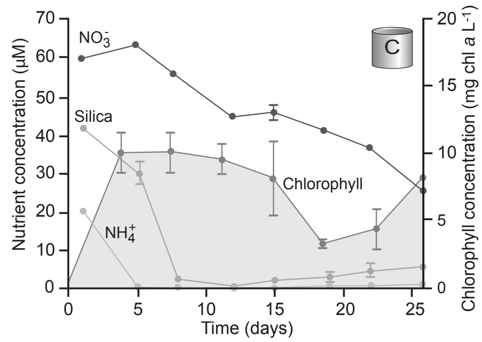


Figure 123: *Representative time courses of changes in NH_4^+, NO_3^-, $Si(OH)^4$, and Chl* a *concentrations from MEERC C tanks. Error bars represent ± 1 standard deviation of three replicate mesocosms.[97] These data show algal growth and nutrient uptake or transformation.*

Table 14: *Potential variables to be sampled in the water column of benthic-pelagic experiments.*

Variables	Utility	Frequency
Temperature	Important control on rate processes, species growth	Continuous to daily
Dissolved O_2	Habitat suitability Production/respiration	Hourly to daily Minutes to hours
NH_3/NH_4	Nutrient uptake or release Ammonia toxicity	Hourly to daily Daily to weekly
Alkalinity/CO_2 system	Production/respiration Carbon limitation	Hourly to daily
Phosphate, Nitrate, and Silicate	Nutrient cycling	Hourly to bi-weekly
Light attenuation through the water column	Limitation of photosynthesis in the water column and of the sediment	Hourly to weekly
Suspended particulates	Resuspension/sedimentation Biogenic particles	Hourly to weekly Daily to weekly
pH	Chemical speciation Toxicity	Daily to weekly
Salinity/major ions	Osmotic balance, habitat suitability	Daily to weekly
Algal pigments	Plant biomass Community composition	Hourly to bi-weekly Weekly
Contaminants	Inhibition of growth or survival	Weekly
Zooplankton adundance and composition	algal grazer community	biweekly to weekly

97. Berg et al. 1999

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