BIOLOGICAL IMPACT ASSESSMENT OF DIRECT CO_2 INJECTION INTO THE OCEAN

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ABSTRACT

Practical implementation of CO_2 sequestration through direct injection of anthropogenic CO_2 into the deep ocean could have a significant environmental impact on marine organisms. In this paper, we summarize recent advances in biological research for direct CO_2 injection and discuss required research work for the future. Possible biological impacts caused by CO_2 storage in the ocean can be categorized into acute and chronic. Acute impacts such as on the survival of marine organisms could be determined by laboratory and field experiments and assessed by simulation models. Chronic impacts, on the other hand, such as sub-lethal effects would be difficult to verify by the same approach as for acute impacts. One of the practical solutions for this issue is field experiments starting with controlled small-scale and, eventually, large-scale CO_2 injection intended to determine ecosystem alteration. Practical implementation of CO_2 ocean sequestration must employ a comprehensive monitoring program of its biological impacts. The ultimate criteria for the actual implementation of marine CO_2 injection will be based on comparison of the biological responses of ecosystems affected by CO_2 between the euphotic zone and the deep sea. Assessment is urgently needed of the comparative differences in marine-ecosystem alterations due to impacts to oceanic euphotic zones induced by the predicted increase in ambient CO_2 levels in the atmosphere over the coming decades and impacts to the deep ocean through direct CO_2 injection to sequester anthropogenic CO_2.

INTRODUCTION

Continuous discharge of CO_2 into the atmosphere will not only accelerate global warming but also raise the partial pressure of CO_2 and lower the pH in the ocean, both of which consequently may result in biological impacts [1, 2, 3]. On the other hand, feasibility studies recently suggest that CO_2 sequestration by direct injection of anthropogenic CO_2 into the deep ocean could help reduce the atmospheric CO_2 concentration and mitigate global warming [4, 5].

Based on the injection depth of CO_2, there are two different principal types of the sequestration technology, i.e. dispersion of CO_2 at intermediate depths (mid-depth type) and injection of CO_2 at depths greater than 3,000 m (lake type) [6]. Irrespective of differences in storage schemes, their implementation could have a significant impact on deep-sea organisms [7].

The environmental/biological impact is the most essential and controversial problem of direct CO_2 ocean-storage technologies. Before implementation of such CO_2-emissions mitigation efforts, a thorough environmental impact assessment is necessary. In this paper, we discuss practical ways of implementing biological impact assessments of direct injection of CO_2 into the deep ocean and indicate the required research strategies.

ACUTE AND CHRONIC IMPACTS

Possible biological impacts caused by marine CO_2 addition can be categorized into acute and chronic. The duration of an acute aquatic toxicity test is generally four days or less and mortality is the response measured. In contrast, a chronic aquatic toxicity test often requires periods from several weeks to years in length and a biological response such as growth is the response measured [8]. When considering direct injection of CO_2, it can be said that acute impacts will mostly occur at and near the CO_2-injection point, whereas chronic impacts will extend over a large area.

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Acute Impacts

Acute impacts such as the effect of elevated CO_2 concentration on the survival of marine organisms can be determined by laboratory [9, 10] and field [11, 12] experiments and assessed by simulation models [13 to 16]. This approach has been developed through the Japanese R&D program [3] although its practicable assessment needs further studies such as those outlined below.

Careful Consideration on Sensitivity-to-CO_2 Differences between Shallow and Deep-Sea Species

Most CO_2-toxicity tests carried out so far have examined the effects on epipelagic species. Development of experimental procedures for deep-sea (mesopelagic, bathypelagic and abyssopelagic) species is needed. There are two basic approaches to conduct such experiments: laboratory and *in situ* studies. A few laboratory [17] and *in situ* studies [11, 12] have been reported. Laboratory studies of living deep-sea organisms require their capture, recovery, and maintenance, and experimental apparatus replicating the deep-sea environment. Laboratory studies have an advantage in that they allow precise control of CO_2 concentration during experimentation (*in situ* studies do not allow this control). Sensitivities of deep-sea species to high CO_2 may be predicted by extrapolation from existing data of well studied epipelagic species, based on the mechanism of the CO_2 effect.

Comparison of Tolerance to High CO_2 Levels and Its Mechanism among Species and Their Developmental Stages

Tolerance of marine organisms to high CO_2 concentrations significantly differs among species and among their developmental stages [9 to 12, 18]. Susceptibilities of marine organisms to high CO_2 are highly relevant to their compensation mechanism. It appears that most invertebrates lack the ability of acid-base regulation to compensate for acidosis associated with high CO_2, whereas fish (vertebrates) have well established compensation mechanisms. Since we have only limited data of CO_2 tolerance of marine organisms, experiments should be conducted on a wide range of taxa. The tolerance should also be examined for various developmental stages of organisms, since their physiology drastically changes with development. A very small decrease in survival during early developmental stages has been shown to cause a large decrease in recruitment success, i.e. significant alteration in population [19].

Examination of Organism Responses under Variable CO_2 Concentrations

Although organisms encountering the high CO_2 plume created by CO_2 injection will experience various CO_2 concentrations for variable durations, the majority of CO_2-toxicity tests so far have been carried out with steady, constant CO_2 concentrations (as is generally the case with conventional toxicity tests). Our recent experiments indicated that mortalities are significantly different between fish exposed to steady and variable CO_2 concentrations (Figure 1). When fish were immediately exposed to CO_2 of 7 kPa water from normocapnic water (steady exposure), all the fish died instantaneously (100% mortality, upper graph of Figure 1). However, mortality of fish was only 30% under a stepwise increase of CO_2 to 7 kPa. In addition to that, the rapid return to normocapnia caused a drastic increase in mortality (lower graph of Figure 1). We hypothesize that the instantaneous death of fish under both a rapid increase and decrease of CO_2 concentration was caused by a disruption of the nervous system associated with acidosis and alkalosis respectively. The lowered mortality under the stepwise increase of CO_2 can be explained by the compensation mechanisms of acidosis through acid-base regulation [9]. Responses by the nervous system occur on a time scale of seconds, whereas acid-base regulation via various physiological mechanisms requires a time scale of at least minutes. Toxicity tests with variable CO_2 concentrations are needed for precise evaluation and prediction of acute impact consequences. The effects of variable ambient CO_2 concentrations should be experimentally re-examined thus avoiding the uncertainties of extrapolating from constant-CO_2 experiments [16, 20].

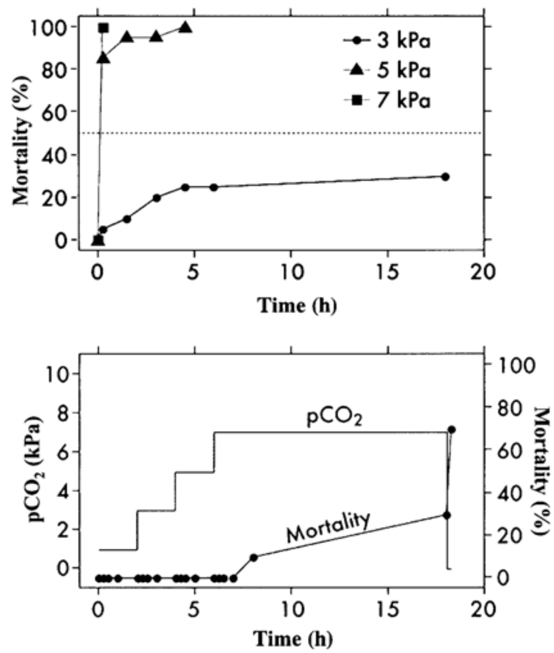

Figure 1: Differences in mortality between fish (*Sillago japonica*, demersal fish of coastal/shallow sea, mean total length ±S.D. = 36.8 ±6.2 mm) exposed to steady and variable CO_2 concentrations (N = 20 for each experiment, Kikkawa, Kita and Ishimatsu, unpubl. data). Upper graph: Mortalities of fish under immediate exposure to CO_2 of 3 kPa (●), 5 kPa (▲) and 7 kPa (■) water from normocapnic water (steady exposure).
Lower graph: Fish were exposed from normocapnic water to CO_2 of 1, 3 and 5 kPa water for 2 hrs in sequences, and to 7 kPa water for 12 hrs, finally to normocapnic water immediately (solid line, variable exposure). Circles (●) with a line indicate mortalities corresponding to variable exposure. Note that the mortality rapidly increases with the immediate return to normocapnia.

Chronic Impacts

Chronic impacts of direct injection of CO_2, i.e. sub-lethal effects of CO_2 on the population dynamics and biodiversity that are directly related to the marine ecosystem, would be difficult to verify by means of laboratory experiments and to assess using ecosystem models. One of the proposed solutions for this issue utilizes field experiments starting with controlled small-scale, and eventually large-scale, CO_2 injection intended to determine ecosystem alteration. Such field experiments can be useful for confirming expected consequences from laboratory experiments and avoiding the uncertainties of extrapolation.

Mid-Depth and Lake-Type Injection Methods

Small-scale field experiments may not be suitable for biological impact studies of mid-depth CO_2-dispersion technology. Since 1) the biomass of the mid-ocean is significantly lower than that of the ocean-floor, and 2) the released CO_2 can rapidly dilute to about 1/50,000 its initial concentration [21], the ecosystem impact would not be at a detectable level within a small-scale experiment. The scale of a field experiment required for detecting ecosystem alteration induced by mid-depth CO_2 dispersion would be on nearly the same scale as the actual implementation scale of the technology.

As regards lake-type CO_2 injection, sluggish and immobile organisms inhabiting the area covered by a liquid CO_2 (lake) would have no chance of survival. The CO_2 plume induced by dissolution of the CO_2 lake would impact the ecosystem in the area around the lake. The ecosystem impact caused by lake-type technology can be assessed by means of small-scale field experiments [11, 12, 22].

As far as species extinction at local and within-short-time scales is concerned, mid-depth CO_2 dispersion would cause less harm than lake-type CO_2 injection. However, lake-type injection of CO_2 into restricted depressions of the seafloor has an advantage in that the biological impacts will be limited to within a relatively local area [23]. Because the scale of the consequences and quality of biological impacts differ between these methods, precise evaluation of which strategy would cause less overall harm needs information about the specific quantity of CO_2 to be injected, which will be determined from economic and technological analysis of these mitigation options,

Determination of Ecosystem Alterations

Although a broad geographical range of deep-sea ecological studies are required for discussion of the feasibility of ocean CO_2 storage, it may be most efficient and effective to start a detailed research project at a regional scale once specific CO_2 injection sites have been proposed. Such a project, whether small or large scale, would need to start by accumulating base-line information through a deep-sea field survey of biomass, biodiversity [24] and the trophic structure (Figure 2) together with collection of physicochemical data, in order to evaluate induced ecosystem alterations. These alterations would be reflected in the food-web structure through changes in the trophic position of organisms. For example, the trophic position of certain omnivorous feeders that feed equally on both lower and higher trophic organisms would shift if their food composition rate of lower/higher trophic organisms were altered by CO_2 injection.

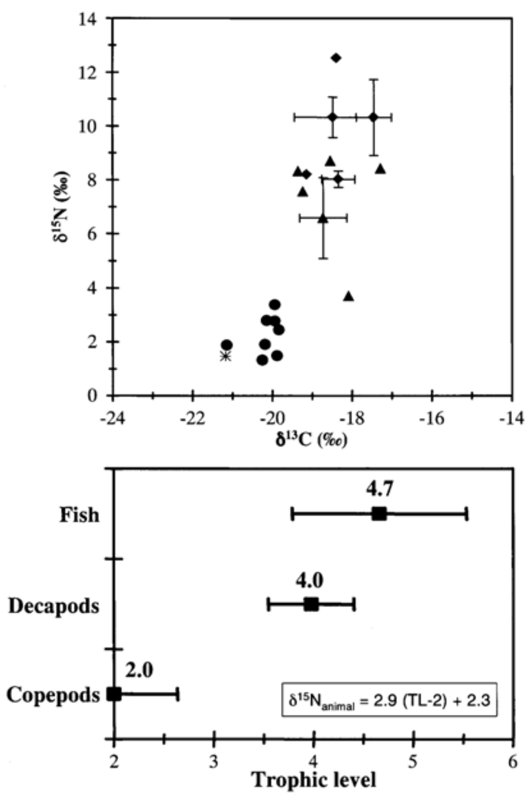

Figure 2: An example of trophic relationships of mesopelagic organisms (Kita and Mito, unpubl. data). Sample organisms were collected from 500 m to 1500 m depth in the sub-arctic area off Japan (36.41N, 141.90E). Upper graph: To avoid variance in $\delta^{13}C$ due to lipid content levels of the organisms, the solvent-extractable lipid fraction was removed from samples for $\delta^{13}C$ analysis. Symbols indicate copepods (●), decapods (▲), salps (*) and fish (□).
Lower graph: Estimation of the trophic level (TL) of copepods, decapods and fish using their $\delta^{15}N$ values. Enrichment value of +2.7 ‰ for $\delta^{15}N$ was used to predict trophic positions.

It should be noted that knowledge of deep-sea ecosystems is fragmentary due to the logistical difficulties of deep-sea research. Therefore analysis of such ecosystems must take notice of new scientific discoveries e.g. the possible high abundances and biomass of gelatinous zooplankton (siphonophores, medusae, ctenophores and salps) in the mesopelagic zone [25] and the importance of the marine microbial ecosystem (microbial-loop) in the physical cycle [26].

The current status of deep-sea ecosystem modelling is still immature because sufficient observational data sets are lacking (Figure 3). Although modelling ecosystem consequences that result from CO_2 additions would be difficult, modelling tools are useful for gaining an understanding of ecosystem structures and mechanisms. Developing a deep-sea, especially a mesopelagic, ecosystem model is also required for the further understanding of the carbon cycle in the ocean. It must be kept in mind that the disappearance of certain species may not influence the overall carbon flux but would nevertheless represent a huge loss to biodiversity.

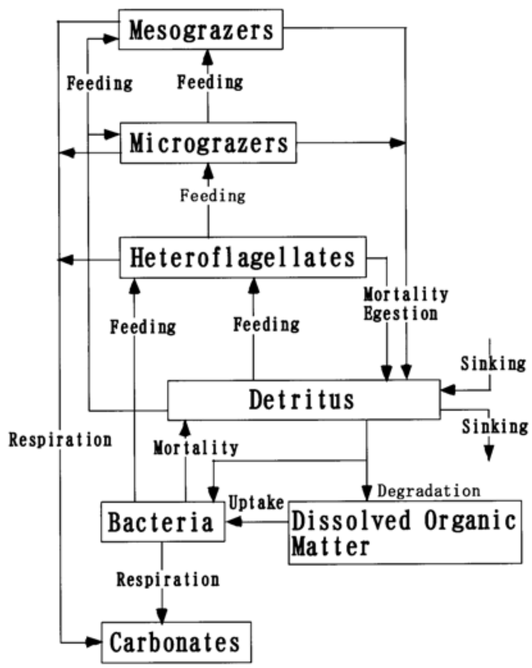

Figure 3: An example of mesopelagic ecosystem model based on the carbon flux. The microbial loop is the main focus in this model. Micrograzers and mesograzers include ciliates and copepods respectively.

Recently an assessment method for the extinction risk to populations induced by toxic chemical compounds has been developed [27 to 29]. Such an approach to ecosystem assessment may be suitable for evaluating the impacts of direct CO_2 injections.

MONITORING OF DIRECT CO_2 INJECTION

As discussed above, acute and chronic impacts on marine ecosystems can be assessed by means of laboratory- and field-experiments and numerical models. However, we cannot avoid pointing out that there is a possibility that environmental impacts of marine CO_2 injection will be larger than we expect. Therefore practical implementation of CO_2 ocean sequestration must, as a precautionary measure, employ monitoring programs for its biological impacts. The monitoring programs should be designed for both acute and chronic impacts. Those for the acute impacts will be restricted to areas near CO_2-injection points and need to be conducted at frequent intervals, whereas those for chronic impacts will be extended over much larger areas, up to basin scale. The area and the frequency of monitoring programs can be configured by numerical models based on the diffusion of injected CO_2.

CONCLUDING REMARKS

The ultimate criteria for the actual implementation of CO_2 injection into the ocean will be established through comparison of responses of the CO_2-affected ecosystems from the ocean surface (impacted by increased atmospheric CO_2 concentration) to the deep sea (impacted by CO_2 injection). Such a comparison based on biological data is urgently needed. It should be taken into account that a considerable amount of the protein source for the world population depends on the marine epipelagic production. It is now well accepted that surface ocean pCO_2 levels will double over their pre-industrial values by the middle of this century and that the marine ecosystem will therefore be impacted [30] regardless of whether or not CO_2 ocean sequestration is implemented.

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