Side Effects of Oceanic Iron Fertilization

OCEANIC IRON FERTILIZATION COULD increase phytoplankton primary productivity in iron-poor oceanic regions, enhancing the carbon flux to the deep sea and drawing excess CO_2 out of the atmosphere. It has been proposed as a way to sequester carbon and thus help to mitigate climate change. S. W. Chisholm and colleagues ("Dis-crediting ocean fertilization," Policy Forum, 12 Oct. 2001, p. 309; and "Response," Letters, 19 Apr., p.467) argue that "manipulations of the oceans at this scale will… alter marine ecosystems dramatically" (19 Apr., p. 468), and therefore "ocean fertilization… should never become eligible for carbon credits" (12 Oct., p. 310) on the global carbon-trading market. Their arguments are based almost exclusively on marine ecology issues. They briefly mention that "the carbon cycle is intimately coupled with those of other elements, some of which play critical roles in climate regulation" (12 Oct., p. 310). The possibility of unintended climatic and atmospheric change, however, is a crucial argument against ocean fertilization that deserves elaboration and public discussion.

Phytoplankton produce dimethylsulfide (CH_3SCH_3 or DMS), an important precursor for maritime sulfate aerosols and cloud condensation nuclei (CCN), which influence cloud properties and climate (*1*–*3*). An increase in phytoplankton primary productivity and thus in DMS levels should lead to cooling of the sea surface waters; the strength of this effect and possible feedbacks on the phytoplankton productivity are presently uncertain (*4*–*6*). Other important chemicals that may also be influenced include volatile organohalogens (*7*, *8*) such as methyl halides (CH_3Cl, CH_3Br, and CH_3I). These photolyze to produce reactive halogens, which are believed to contribute to lower stratospheric O_3 depletion (*9*), as well as to marine boundary layer O_3 destruction (*10*, *11*). Finally, carbonyl sulfide (*12*) (OCS) contributes to the stratospheric aerosol layer (*13*) and thus to heterogeneous O_3 loss. An increase in these gases would enhance stratospheric ozone depletion and lead to intensified ultraviolet levels at Earth's surface, with possible biological health consequences (*14*).

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Ocean fertilization could also directly affect the atmosphere-ocean system radiative budget. The extreme scenario of removing 600 µmol/mol of atmospheric CO_2 over a period of 100 years by fertilizing 30% of the world's oceans would require a sustained increase in photosynthetic energy equivalent to ~1.5 W/m^2 over the fertilized region (*15*). Most of this would be transferred as heat to the ocean's surface waters via respiration (*15*), increasing regional sea surface temperatures. However, as Chisholm *et al.* point out, this scenario for complete removal of anthropogenic CO_2 may not even be realizable unless limitations on the availability of N and P were also overcome.

One could imagine many other possible climate effects, such as ocean circulation changes due to modified surface water temperatures and salinity (via brine content). Nevertheless, K. S. Johnson and D. M. Karl ("Is ocean fertilization credible and creditable?", Letters, 19 Apr., p. 467) have suggested that "[i]t is simply not credible, or creditable, to suggest that we know enough to understand the impacts of ocean fertilization at the present time." Although, indeed, we cannot predict exactly what would happen after a given fertilization scenario, Johnson and Karl do not give sufficient credit to our knowledge about the wide range of side effects with various probabilities. It is hard to believe that the developers of any profit-driven commercial CO_2 draw-down strategy would voluntarily assess and (where possible) avoid environmental side effects. Could such a task be accomplished by an intergovernmental body (e.g., UNEP)? Perhaps, but it seems that the resources necessary for fertilization, logistics, and assessment programs would be better spent on more pressing problems, such as new measures to reduce CO_2 emissions. In any case, Chisholm *et al.* should be lauded for their efforts toward ensuring that basic science, rather than market interests, drives future research on marine ecology and its relationship to the climate.

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15. Photosynthesis is endothermic, requiring 686 kcal/mol ($C_6H_{12}O_6$), or 1.1×10^7 J/kg (CO_2). Because only about 10% of the carbon involved in photosynthesis is removed as fecal pellets and not recycled in the surface waters (*16*), the photosynthetic energy per unit area required is $E = 10 \times 1.1 \times 10^7$ J/kg (CO_2) x M (CO_2)/($A_{ocean} \times \tau$), where M (CO_2) is the mass of atmospheric CO_2 to be removed, A_{ocean} is the oceanic surface area over which the fertilization would take place, and τ is the time period over which the removal should occur.
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Letters to the Editor

Letters (~300 words) discuss material published in *Science* in the previous 6 months or issues of general interest. They can be submitted by e-mail (science_letters@aaas.org), the Web (www.letter2science.org), or regular mail (1200 New York Ave., NW, Washington, DC 20005, USA). Letters are not acknowledged upon receipt, nor are authors generally consulted before publication. Whether published in full or in part, letters are subject to editing for clarity and space.

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Critical Challenges for Sustainability Science

KATES *ET AL.* ADVOCATE THE DEVELOPMENT of a new "sustainability science" ("Sustainability science," *Science*'s Compass, Policy Forum, 27 Apr. 2001, p. 641). As world development moves in unsustainable directions, it is indeed timely to expand the structure and focus of the scientific enterprise to effectively address emerging questions. The urgency for a transition to sustainability and the associated need for new directions in science had earlier been stressed by the Board on Sustainable Development of the U.S. National Academy of Sciences (*1*). However, although the proposed core research questions of sustainability science are apt, they are insufficient.

Kates *et al.* list four methodological challenges: (i) spanning the range of spatial scales; (ii) accounting for temporal inertia and urgency; (iii) dealing with functional complexity and multiple stresses on human and environmental systems; and (iv) recognizing the wide range of outlooks. We would expand this list of challenges to include (v) linking themes and issues (e.g., poverty, ecosystem functions, and climate); (vi) understanding and reflecting deep uncertainty; (vii) accounting for human choice and behavior; (viii) incorporating surprise, critical thresholds, and abrupt change; (ix) effectively combining qualitative and quantitative analysis; and (x) linking with policy development and action through stakeholder participation.

Sustainability science will need to transcend the determinism and incremental responses to perturbation that still dominate much research on the dynamics of combined socio-ecological systems. The evolution of methods that can adequately and rigorously capture uncertainty, the capacity for system discontinuity, and the normative content of sustainability problems defines a rich and urgent research agenda. In this regard, participatory scenario development offers one approach for systematically addressing many of the core challenges identified above. This method has been used in various contexts, such as the work of the Global Scenario Group (*2*), which has been used for UNEP's Global Environmental Outlook (*3*), and the work of the Intergovernmental Panel on Climate Change (*4*), and at a regional scale in the Georgia Basin Futures project (*5*). Such exercises have proven successful in bridging gaps between science and policy by engaging a wide range of experts and stakeholders in a systematic exploration of diverse global futures.

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Response

WE THANK SWART *ET AL.* FOR THEIR INTEREST in elaborating on the scientific core questions of sustainability science and the challenge of appropriate methods and approaches. We agree with many of their arguments and, indeed, addressed several of them as substantive (rather than methodological) challenges in our Policy Forum. More importantly, however, the meeting reported in our Policy Forum catalyzed a process of consultations on science, technology, and sustainability that, over the past year, has engaged more than 300 scientists and technologists from more than 40 countries in locally organized workshops on every continent except Antarctica. These consultations have reviewed the relevance of the core questions and challenges posed in our Policy Forum to the most urgent sustainability problems of specific regions. A synthesis workshop, organized in collaboration with the International Council for Science (ICSU) and the Third World Academy of Sciences in May, sought to integrate these regional perspectives and identify priority measures for harnessing science and technology in support of sustainability. The report of that meeting has been taken forward by ICSU as a contribution to the World Summit on Sustainable Development.

Results of this continuing process of revision and elaboration can be found on the Forum on Science and Technology for Sustainability at sustainabilityscience.org. Each of the core questions initially raised in our Policy Forum now has a separate Web page with introductory essays, commentary, links, and resources. Emerging thinking on a number of related issues, including several of those raised by Swart *et al.*, is also addressed. Finally, the Forum supports a growing network of scientists and technologists interested in specific questions of science, technology, and sustainability.

We invite all *Science* readers to peruse these discussions on the Forum, join the network, comment on any or all of the many papers and documents posted, and further the development of the virtual community of sustainability science and technology.

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Does the Sun Know What Day It Is?

I WAS AMUSED BY THE RANDOM SAMPLES item "Sun burp" (12 July, p. 189), in which it is stated, "The sun jumped the gun on Independence Day fireworks, belching out a massive curling cloud of flaming gas more than 30 times Earth's diameter on 1 July." Do you have some unreported evidence that the sun is American? Many countries celebrate their national day with fireworks, and several do so on July 1, including your neighbor to the north. Perhaps the sun is really Canadian, eh?

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Making a Case for Conservation

I THINK IT'S IMPORTANT WHEN SCIENTISTS with the credentials of *Science*'s Editor-in-Chief Donald Kennedy make an effort to portray scientific evidence in terms the public can understand, as he did in his recent Editorial "POTUS and the fish" (26 July, p. 477) about President Bush and daughter Jenna's striped bass capture during a Maine vacation this summer.

I have absolutely no quarrel with Kennedy's comments regarding the extension of species' ranges as a result of climatic change, but I'm not sure the striped bass incident he cites is a case in point. *Morone saxatilis* is a broadly distributed species. Old ichthyology texts list its range from Louisiana in the Gulf of Mexico up to the New Brunswick coast of Canada—well within the area of the Bush expedition. In the 1950s, I worked as a mate on a charter boat that fished in huge schools of stripers in Cape Cod (now Massachusetts) Bay, north of the Cape. By the time I began doing research at the Marine Biological Laboratory in Woods Hole in the late 1960s, not only were stripers in decline north of Cape Cod, as Kennedy indicates, but by the late 1980s, only the old salts were able to catch stripers south of the Cape, and then not reliably. The North Atlantic population of *M. saxatilis*, most of which originates in the Chesapeake and Delaware Bays, had entered a period of steep decline. There were few striped bass anywhere along the Atlantic coast, outside of hatcheries.

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President Bush and daughter Jenna catching a striped bass in Maine this summer.

CREDIT: ROBERT F. BUKATY/AP

While I'm not sure if the problem causing the decline was actually ever identified—there were the usual handwringings and accusations of pollution versus overfishing (both likely to blame)—in 1981, a massive striped bass conservation effort was undertaken by the Atlantic States Marine Fisheries Commission (ASMFC), which developed and adopted a striped bass management plan involving states from Maine to North Carolina. This effort seems notable to me, not only for its success, but also for the incredible cooperation that was ultimately achieved among several state and local governments, commercial and local fishermen, restaurateurs, and biologists. Instead of global warming, I think it's more likely that the Bushs' catch, especially because the first family was fishing well within the native range of the species, was due to this major conservation effort coupled with a very successful *M. saxatilis* spawn in the Chesapeake Bay several years ago. Indeed, the conservation effort was so successful that the ASMFC declared the Chesapeake Bay stock of Atlantic striped bass, which supports the greatest portion of the Atlantic coastal stock, recovered as of 1 January 1995 (*1*). Still, I hope the lesson will not be lost on the president. Conservation and management of natural resources, along with a helping hand from nature, can work in at least some cases.

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Reference

1. See www.asmfc.org.

Response

I SHOULD HAVE GIVEN MORE CREDIT TO striped bass conservation, which Pierce properly praises for having boosted populations all along the Atlantic Coast. Henry Bigelow's classic *Fishes of the Gulf of Maine* documents that populations along the Maine coast were relatively low compared with those south of Cape Cod before World War II, but included numbers of Chesapeake and Delaware migrants in "good years." Recent conservation-based improvement in bass reproductive success doubtless contributed to making the Bush fishing trip a success. But the impact of climate change on the distribution of other marine species strongly supports the idea that northward range extension was at work for stripers as well.

DONALD KENNEDY

CORRECTIONS AND CLARIFICATIONS

SPECIAL ISSUE ON POLAR SCIENCE: NEWS: "Breaking up is far too easy" by J. Kaiser (30 August, p. 1494). A map of recent ice shelf losses on the Antarctic Peninsula (p. 1495) should have indicated that a portion of the Larsen B shelf is still intact (see map).

Image not available for online use.

NEWS FOCUS: "Protecting the brain while killing pain?" by L. Helmuth (23 Aug., p. 1262). The results of research by Edward Koo, Todd Golde, and colleagues were misrepresented. The drugs rofecoxib and naproxen do not increase the production of β amyloid 42 in cell cultures and animal studies as *Science* reported. The two drugs have no effect on the ratio of β amyloid 42 to other β amyloid species. As the article noted, all experiments showing an effect of nonsteroid anti-inflammatory drugs on β amyloid production used very high doses.

NEWS OF THE WEEK: "Tough challenges ahead on political and scientific fronts" by J. Cohen (19 July, p. 312). Cohen quoted U.S. Secretary of Health and Human Services (HHS) Tommy Thompson as saying he was the first person in his job who had "had the courage" to attend the international AIDS conference in 12 years. In fact, HHS Secretary Donna Shalala gave a plenary speech at the international AIDS conference held in Vancouver in 1996.