vivorship and seed mass over two generations.

Biomass was almost always greater in the first-generation offspring of crosses involving foreign material, but declined in the second generation. Mortality was higher in both generations. Seed weight, like biomass, was generally higher in the first generation and lower in the second generation of foreign crosses. So it seems that, in the long term, the introduction of foreign genes into these weed populations is likely to make them less fit — that is, less able to survive and reproduce effectively. Relative reductions in fitness were estimated to be between 8% and 23%. The overall message is that the introduction of genes from distant populations is likely to do lasting harm to the native weed flora of an area.

These findings have broader implications. The introduction of fresh breeding stock into fragmented and isolated populations is often seen as a way of increasing genetic diversity, and has been attempted in organisms ranging from butterflies to birds[2]. The merits of such a policy can vary with the geographical distance from which introduced material is obtained and with the spatial variability in the genetic constitution of the species concerned. Geographical distance might not always correspond to genetic distance: it will also vary with the type of organism involved.

The effects of genetic distance have been tested on a Californian shrub, *Lotus scoparius*, the deerweed[3], using degrees of enzyme variation as the genetic measure. Deerweed is a variable shrub of the coastal sage community of the west coast of North America, being found in both arid and well-watered habitats. In an experiment involving 12 populations, there was only weak correlation between geographical and genetic distances. But in transplant experiments the cumulative fitness of plants showed an inverse relationship to genetic distance. The closer the relationship is, the more likely it is that the individual will survive well in similar situations. So the introduction of this shrub should be determined by an analysis of genetic or ecological similarity (or both): geographical proximity of a seed source will not necessarily provide the most appropriate material for translocation.

A further complication with flowering plants arises from their different breeding strategies. The corncockle, for example, often self-pollinates, so its genetic constitution is likely to be patchy on a local scale. Deerweed is pollinated by insects, which might also restrict the distances over which outbreeding is possible.

How does this relate to wind-pollinated, outbreeding plants such as birch, poplar, alder and elm? A modelling exercise, based on data concerning the timing of flowering and its response to climate[4], has shown that there is little evidence of local genetic variation in these and other tree species across Europe. The production of large amounts of pollen and the potential for distant dispersal in these species ensures rapid gene flow and little opportunity for local isolation and adaptation. In such outbreeding species, one could argue, the problems of selecting appropriate stock for sowing or transplanting in new locations are less serious.

The history of plant and animal introductions is littered with catastrophes[5]. These reports concerning the implications of moving genes between populations suggests that caution is needed here also. ■

Peter D. Moore is in the Division of Life Sciences, King's College London, Franklin–Wilkins Building, 150 Stamford Street, London SE1 8WA, UK.
e-mail: peter.moore@kcl.ac.uk

1. Keller, M., Kollmann, J. & Edwards, P. J. *J. Appl. Ecol.* **37,** 647–659 (2000).
2. Evans, E. I. *et al. Br. Birds* **90,** 123–138 (1997).
3. Montalvo, A. M. & Ellstrand, N. C. *Conserv. Biol.* **14,** 1034–1045 (2000).
4. Chiune, I., Belmonte, J. & Mignot, A. *J. Ecol.* **88,** 561–570 (2000).
5. Macdonald, I. A. in *Biodiversity and Global Change* (eds Solbrig, O. T., van Emden, H. M. & van Oordt, P. G. W. J.) 199–209 (CABI, Wallingford, Oxon, 1994).

Oceanography

Stirring times in the Southern Ocean

Sallie W. Chisholm

Almost half of the photosynthesis on Earth is carried out by phytoplankton in the sea. So these tiny cells play a huge part in the global carbon cycle, and in regulating climate by controlling the amount of the greenhouse gas CO_2 in the atmosphere. Phytoplankton are the engine of the 'biological pump' (Fig. 1) that helps maintain a steep gradient of CO_2 between the atmosphere and deep ocean. It has been suggested that we

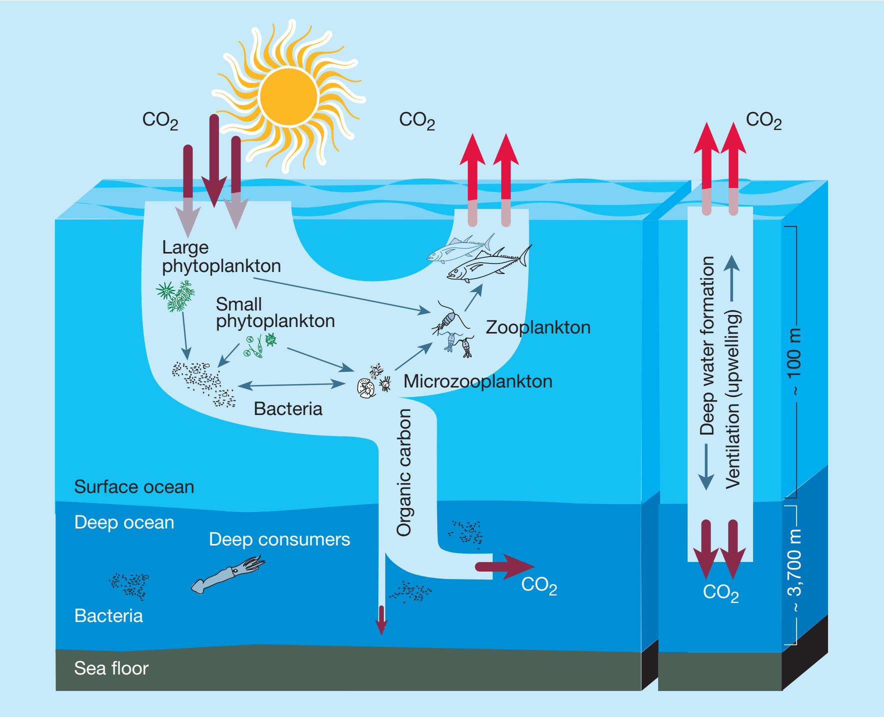

Figure 1 **The 'biological pump' is a collective property of a complex phytoplankton-based food web. Together with the 'solubility pump' (right), which is driven by chemical and physical processes, it maintains a sharp gradient of CO_2 between the atmosphere and the deep oceans where 38 × 10^{18} g of carbon is stored. Using sunlight for energy and dissolved inorganic nutrients, phytoplankton convert CO_2 to organic carbon, which forms the base of the marine food web. As the carbon passes through consumers in surface waters, most of it is converted back to CO_2 and released to the atmosphere. But some finds its way to the deep ocean where it is remineralized back to CO_2 by bacteria. The net result is transport of CO_2 from the atmosphere to the deep ocean, where it stays, on average, for roughly 1,000 years. The food web's structure and the relative abundance of species influences how much CO_2 will be pumped to the deep ocean. This structure is dictated largely by the availability of inorganic nutrients such as nitrogen, phosphorus, silicon and iron. Iron is the main limiting nutrient in the Southern Ocean, which is why the SOIREE experiment[1–3] was conducted there. (Figure modified from a graphic by Z. Johnson.)**

100 YEARS AGO

The New York correspondent of the *Lancet* states that the Chicago Board of Education has established a department called "Child-study and Pedagogic Investigation". The examination is undertaken for the purpose of determining the mental and physical status of the school-children. Examinations were at first limited to the determination in each pupil of the following points: Height, height sitting, weight, ergograph work, strength of grip right and left, hearing right and left, and acuity of vision. In addition to this, obvious developmental defects have been noted. The number of children examined down to the present time is 5636. The conclusions thus far reached are that there is a physical basis of precocity, that dull children are lighter and precocious children heavier than the average child, and that mediocrity of mind is associated with mediocrity of physique… This is the first instance of a municipal board in America appropriating money for research work, and its effect may be far-reaching.

From *Nature* 11 October 1900.

50 YEARS AGO

There has probably never been a time in the history of the oil industry when 'petrol', to use the colloquial term, has engaged so forcibly public attention in Great Britain and elsewhere. Once rationing is imposed on any commodity which has been taken for granted, as up to 1939 petrol certainly was and likewise food (water has always been), there is solid basis for the ordinarily complacent citizen to know the reason why and to bestir himself to the facts. Even to keep a ration going for vital needs in time of emergency and stress is a formidable task; had it not been for amazing advances in technique of producing motor fuels by processes developed during the Second World War and afterwards, one wonders whether, indeed, economic factors aside, the petrol ration would not be with us in Britain and in Europe generally for years to come. The explanation of these advances is, of course, highly technical; it rests on the extraordinary rate of evolution in refinery procedure during the past decade and on conversion of petroleum in the more or less raw state into motor fuels by specialized thermal and catalytic processes. Dr. A. N. Sachanen devotes his large book to this complex subject and to the technologist.

From *Nature* 14 October 1950.

might increase the efficiency of this pump — thereby drawing more CO$_2$ out of the atmosphere — by artificially supplying nutrients to the surface oceans. This suggestion is highly contentious. Papers by Boyd *et al.*[1], Abraham *et al.*[2] and Watson *et al.*[3] (pages 695, 727 and 730 of this issue) will add fuel to the debate about the desirability of such 'geoengineering' solutions to Earth's ills. The papers describe the results of a fertilization experiment in the Southern Ocean, around Antarctica, and its scientific implications for interpreting past climate change.

Phytoplankton biomass in the global oceans can usually be correlated with the supply of nitrogen, phosphorus and silicon upwelling from the deep sea to the sunlit surface waters where photosynthesis takes place. In the equatorial Pacific and the Southern Ocean, however, these supplies far exceed demand, indicating that some other factor is limiting phytoplankton growth. This mystery plagued oceanographers for decades until the late John Martin showed that the limiting factor is iron, a trace element that reaches the oceans in atmospheric dust[4]. Analyses of ancient ice cores show that dust deposition varied significantly during glacial and interglacial periods, and is anticorrelated with concentrations of atmospheric CO$_2$ over the past 400,000 years. So Martin reasoned that airborne iron supply could in part regulate climate by increasing the efficiency of the biological pump. He further suggested that very small amounts of iron distributed in today's Southern Ocean could draw a significant amount of CO$_2$ from the atmosphere. This is partly because the Southern Ocean is huge and, apart from iron, holds vast quantities of unused nutrients, and partly because its surface waters tend to sink, delivering carbon to the deep ocean.

With this as a backdrop, Boyd *et al.*[1] launched the SOIREE expedition (for Southern Ocean iron release experiment) in February 1999. They distributed 8,663 kg of an iron compound over a patch of ocean 8 km in diameter, some 2,000 km south-south-west of Hobart, Tasmania. The experiment was a dramatic success. Physiological indicators of iron stress decreased in the

Box 1 Commons concern

Whole-ecosystem experiments have revolutionized ecology[9]. With three successful ocean-fertilization experiments[1,5,10], oceanographers have joined that revolution. The discovery that iron limits phytoplankton growth in the equatorial Pacific and Southern Ocean has made it possible to stimulate the productivity of hundreds of square kilometres of ocean with a few barrels of fertilizer. By contrast, it would take roughly 3,000 times as much nitrogen and phosphorus to fertilize the North Atlantic, where these elements are limiting.

This is a powerful new tool for oceanographers, because by transient perturbation of the ecosystem from its quasi-equilibrium state we can glimpse the mechanisms that keep it there. These mechanisms, which consist of tightly coupled production and consumption processes in a complex food web (Fig. 1), hold one of the keys to understanding the connection between the oceans and the climate.

With powerful tools comes the responsibility of deciding how to use them. Small-scale scientific experiments are one thing. But the correlations between iron availability, marine productivity and climate change have led to the prospect of using ocean fertilization to manipulate climate.

Coupled with the post-Kyoto possibility of a global market in carbon emissions trading, including the issuing of 'carbon credits'[11], this idea has spawned a budding industry[12,13]. Patents on ocean fertilization have been issued to entrepreneurs and large corporations[14], and there are plans for a 8,000-km^2 'demonstration experiment'[15]. With a few exceptions[16], little attention is being paid to the risks of large-scale fertilization. But we will be forced to make decisions about this technology, and quickly, whether we are ready or not.

In deciding on future uses of the ocean Commons, we have an opportunity to learn from past mistakes. The oceans are a complex adaptive system, so it is impossible to predict the long-term consequences of commercial ocean fertilization. How then can we decide whether to proceed? We need to "reach for lessons"[17].

The Earth system consists of elements distributed between the land, air and oceans by biological and geological processes over millions of years. Many environmental problems stem from our moving elements between these compartments at unprecedented rates that the system cannot accommodate. Importing massive quantities of nitrogen from the atmosphere to the land through fertilizer production, for example, has increased the production of the greenhouse gas nitrous oxide, and destroyed the ecology of coastal waters. Burning fossil fuels has moved massive amounts of carbon from the land to the atmosphere, and threatens to warm the globe. The direct and large-scale fertilization of the sea would undoubtedly have similar unintended consequences. The lesson is simple. In the long run, ocean fertilization is not sustainable. So why start? **S. W. C.**

iron-enriched patch within two days. Primary productivity, phytoplankton carbon and chlorophyll levels increased slowly but steadily over the 13 days that the patch was monitored, drawing nutrients and CO_2 from the surface waters. The result was a tripling of phytoplankton chlorophyll by the end of the experiment. These results are qualitatively much like those from a similar experiment[5], conducted in the equatorial Pacific in 1995, but the development of the phytoplankton bloom was much slower and its magnitude smaller. The increase in phytoplankton biomass resulted in large part from a shift in the phytoplankton community from small- to large-celled species, primarily diatoms, which can outgrow their predators when suddenly released from nutrient limitation.

What was the long-term fate of the patch? From satellite pictures, Abraham *et al.*[2] demonstrate that a month after the end of the experiment the patch still had chlorophyll levels that were three times background concentrations, and had been transformed into a ribbon 150 km long and 4 km wide by stirring and diffusion. It stayed intact for at least two more weeks, having accumulated an estimated 600 to 3,000 tonnes of algal carbon. As the authors point out, however, there is no evidence that any of this carbon was exported to the deep ocean, as would be required for drawdown of atmospheric CO_2. In fact, over the period of the SOIREE measurements, the carbon export rates from the fertilized patch were actually lower than those of the surrounding waters, in part because diatom cells get lighter when released from iron starvation, and settle more slowly.

So SOIREE provides no evidence that iron fertilization increases carbon export from the surface to deep ocean. How then do these results relate to Martin's hypothesis that iron supplies to the Southern Ocean drive glacial–interglacial transitions? Watson *et al.*[3] make this link using a model of the ocean–atmosphere carbon cycle to examine the effects of fluctuating iron supplies on atmospheric CO_2 concentrations over the past 400,000 years. They constructed the model using parameters drawn from SOIREE, 'forced' it with atmospheric iron fluxes derived from ice-core data, and compared the simulated atmospheric CO_2 concentrations with those measured in the ancient ice. The model reproduced the timing of glacial–interglacial fluctuations in atmospheric CO_2 remarkably well, challenging claims[6] that the lag between the iron and CO_2 fluctuations in the ice core is too long for the relationship to be linked directly through Southern Ocean productivity.

One conclusion drawn by Watson *et al.* from their analysis is that "modest sequestration of atmospheric CO_2 by artificial additions of iron to the Southern Ocean is in principle possible", supporting Martin's suggestion and the results of models designed to examine this possibility[7]. Although seductive in its simplicity, in practice this idea would threaten the ocean ecosystem (Box 1). Artificial fertilization with iron would probably have many unintended side effects, such as deoxygenating the deep ocean[7] and generating greenhouse gases that are more potent than CO_2 (ref. 8). We know that it would change the structure of the marine food web.

Global biogeochemical cycles of elements have been shaped by the forces of evolution over geological timescales, and are tightly coupled. The injection of a single element (iron) into this system over a period of years to decades is not the same as the natural delivery of atmospheric dust to the oceans over thousands of years. Moreover, we cannot expect to change the flux of carbon from the atmosphere to the oceans — a single 'arrow' in this complex, self-organized system — without changing other features of the system in undesirable ways. It is likely that we would not recognize these changes until it was too late to reverse them. ■

Sallie W. Chisholm is in the Department of Civil and Environmental Engineering, and the Department of Biology, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.
e-mail: chisholm@mit.edu

1. Boyd, P. W. *et al. Nature* **407,** 695–702 (2000).
2. Abraham, E. R. *et al. Nature* **407,** 727–730 (2000).
3. Watson, A. J., Bakker, D. C. E., Ridgwell, A. J., Boyd, P. W. & Law, C. S. *Nature* **407,** 730–733 (2000).
4. Martin, J. H. in *Primary Production and Biogeochemical Cycles in the Sea* (eds Falkowski, P. & Woodhead, A. D.) 123–138 (Plenum, New York, 1992).
5. Coale, K. *et al. Nature* **383,** 495–501(1996).
6. Broecker, W. S. & Henderson, G. M. *Paleoceanography* **13,** 352–364 (1998).
7. Sarmiento, J. & Orr, J. *Limnol. Oceanogr.* **36,** 1928–1950 (1991).
8. Fuhrman, J. A. & Capone, D. G. *Limnol. Oceanogr.* **36,** 1951–1959 (1991).
9. Carpenter, S. R. *et al. Science* **269,** 324–327 (1995).
10. Martin, J. A. *et al. Nature* **371,** 123–148 (1994).
11. Ney, R. A. & Schoor, J. L. *Env. Sci. Technol.* **34,** 177A–182A (2000).
12. Jones, I. S. F. & Otaegui, D. *Energy Conv. Mgmt* **38,** S367–S372 (1997).
13. Markels, M. *Regulation* **21,** 9–10 (1998).
14. www.uspto.gov Patent nos 6056919, 5992089, 5965117
15. Rawls, R. *Chem. Eng. News* 18 September, 66–69 (2000).
16. http://esd.lbl.gov/DOCS/index2.html
17. Goldenfeld, N. & Kadanoff, L. *Science* **284,** 87–89 (1999).

DNA repair

Guarding against mutation

Richard D. Kolodner

Accurate duplication of a cell's DNA is essential for the viability and normal growth of that cell. But DNA replication occurs frequently and is complicated, so errors occur. This often results in incorrect pairing of the chemical bases that make up the rungs of a DNA ladder. If these mistakes are not fixed, harmful mutations can accumulate, so the error-correcting — 'mismatch-repair' — proteins are crucial. Defects can also occur in the genes encoding these proteins, resulting in high mutation rates and other damaging effects. For example, inherited defects in some human mismatch-repair genes cause a common syndrome characterized by a predisposition to cancer, and some sporadic cancers are due to defects in mismatch-repair genes that occur during normal cell growth[1]. Key proteins in the mismatch-repair process are those that actually recognize the mispairs[2,3]. The structural basis of this recognition process is revealed — for two bacterial proteins — by Obmolova *et al.*[4] and Lamers *et al.*[5] on pages 703 and 711 of this issue.

There are several mispair-recognizing proteins. In bacteria, these include the MutS protein — that studied by Obmolova *et al.*[4] and Lamers *et al.*[5]. Here, two identical MutS proteins interact to form a functional 'homodimeric' complex. In eukaryotic organisms, such as humans, two different MutS-related proteins (such as MSH2 and MSH6, or MSH2 and MSH3) interact to make up a 'heterodimeric' complex[2,3].

Proteins of the MutS family are remarkable sensors of DNA damage. The eukaryotic MSH2–MSH6 complex can detect several types of errors in DNA, with different consequences. For example, mispaired bases that arise as a result of DNA-replication errors are recognized by this complex, and repaired by mismatch repair[2,3]. Another type of mispaired base — that resulting in reproductive and other dividing cells when similar chunks of chromosomes are swapped around by a process called recombination — is similarly fixed by mismatch repair[2,3]. By contrast, when these recombining chromosome segments are too dissimilar, a different outcome ensues: the prevention of recombination[2,3,6].

Finally, eukaryotic MutS proteins can recognize chemical damage in DNA, including that caused by some drugs used for chemotherapy. This can activate cell-death pathways rather than DNA repair. Defects in this process result in cellular resistance to these drugs, and the resistance of cancer to chemotherapy[7,8]. So, if we can unravel how the MutS proteins distinguish between so many types of problematic DNA structure, and communicate specifically with so many downstream pathways, we will not only gain greater insight into a fundamental biological process, but may also learn more about