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Biotechnology for environmental quality: closing the circles

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This paper examines the impact of biotechnology for enhancing the quality of the environment, and the necessity of encouraging holistic approaches to environmental problem solving. Current actions are considered wanting because they place insufficient attention on the causes of environmental degradation. In this context, a number of issues and research agendas are presented, a consideration of which leads me to opine that urgent priorities for ensuring lasting sustainable development must include the widespread adoption of clean technology and ecosystem restoration. Biotechnology has a particularly decisive role to play in realizing clean processes and clean products, and this role is illustrated with reference to clean technology options in the industrial, agroforestry, food, raw materials, and minerals sectors. A quarter of a century ago Commoner (1971) used the metaphor of a closing circle to draw attention to incompatibilities of modern industrial society and ecological health. The second part of this paper argues that, as biotechnology has matured, a circle of synergistic flows of materials, services and ideas has been established between it and biodiversity and suggests a more optimistic scenario to that portrayed by Commoner. The closing of the biotechnology–biodiversity circle is manifest in the following terms: search and discovery; detection, circumscription and phylogeny; ecosystem function and restoration; industrial ecology; and the gearing provided by molecular biology. Finally, the North–South biotechnology–biodiversity circle presents critical problems of commercial exploitation and intellectual property rights in relation to the gene pools of the megadiversity but predominantly developing countries of the world.

Keywords: biotechnology; biodiversity; environmental degradation; pollution; clean technology; industrial ecology; ecosystem restoration.

Introduction: definitions and scenarios

The end of the millennium is being assailed by a plethora of environmental problems. The situation is stated cogently by Callicott (1994),

> 'The environmental crisis – discovered in the industrial West in the 1960s, plastered over with regulative legislation in the 1970s, then forgotten only to return with a vengeance in the 1980s – is now global in scope and focus. South and East Asian countries have become full-fledged members of the club of industrial nations, widening the scope of the crisis. In the 1960s ... the focus of the nascent environmental concern was local – primarily on point-source pollution ... broadcast pesticides ... and oil spills. Now the focus of environmental concern is holistic and systemic – centering on the integrity of the planetary ecosystem ... (it) ... is so pervasive that it cannot be ignored.'

In this paper I attempt to gauge the impact that biotechnology might have in alleviating some of these problems, how it might assist in resolving the dilemmas that confront this uniquely biological planet, and to suggest research and development agendas for action.

Are there ways by which biotechnology might redress some of the incompatibilities of modern industrial society and ecological processes articulated in Commoner's (1971) *Closing Circle*? Thus a recurring theme of this paper is the need to adopt holistic approaches to environmental problem-solving if biotechnology is to deliver those beneficial effects being predicted by many scientists, technologists and commentators.

First, it seems prudent to establish some terms of reference. 'Biotechnology' was defined a decade ago by the OECD as 'the application of scientific and engineering principles to the processing of materials by biological agents to provide goods and services' (Bull *et al.*, 1982); while acknowledging its ability to open up new horizons for human activity, and to solve certain problems, biotechnology was not proposed as a universal panacea, a conclusion which still remains valid and is usefully restated. The 'environment' literally (*en* within, *viron* circle) is everything and everywhere within the circle; as Moore (1994) has recently impressed, it is a term used habitually but one often impoverished by a restricted context. 'Environmental quality', therefore, defines the measure of excellence or well-being (or otherwise) of the whole circle, *viz.* the biosphere, and the means whereby it can be sustained. 'Sustainability' and 'sustainable development', while they are terms that convey ambiguity and invite a plurality of interpretation and implementation, nevertheless encapsulate and reiterate the need (even acceptance) for an environmental ethic. The basic Brundtland definitions have stood the test of time (meeting the needs of the present without compromising the ability of future generations to meet their own needs; and, at very least, not endangering natural systems that support life on Earth) although the proposals for institutional reform on which sustainable development was conceived still remain to be activated fully (Brundtland, 1987).

Further attention must be given to the task of defining broadly acceptable indicators of sustainability: 'human development index'? (embracing longevity, knowledge, income), an 'index of sustainable economic welfare'? (which adjusts gross national product to account for depletion of natural capital, pollution burden, income distribution effects), or an 'ecological footprint'? (which accounts for the amount of land, or water, that is needed indefinitely to generate necessary resources and to assimilate the resultant wastes of the sustained community). A succinct and thoughtful evaluation of sustainable development and how the recommendations of the Brundtland Commission have been progressed is provided by O'Riordan (1995). Arguably, therefore, the greatest challenge for humanity now is how to ensure sustainability in the face of a changing biosphere and to understand how to achieve homeostasis on a planetary scale.

Few would disagree with Speth's statement that present approaches will not accomplish the goal of environmental sustainability because they fail to focus sufficiently on the underlying causes of environmental problems (Speth, 1992). Thus, while the massive consumption of non-renewable (finite) resources has featured prominently in environmental debates, it is renewable resources – the indefinitely regenerating 'free goods' of nature – and the systems that sustain them that are under the greatest threat of degradation or even extinction. The inventory of these renewable resources includes: (1) stable climate, (2) clean air, (3) clean fresh and marine water, (4) fertile soils, and (5) genetic diversity and the ecosystem functions which it provides. The consequences of their misappropriation are manifest as global warming, massive and new assaults on human health, desertification, threats to the provision of food, feed, fuelwood, and increased risks of flooding and watershed disruption; and which, in turn, have their origins in epidemic contamination by wastes and toxic chemicals, deforestation, ill-conceived agricultural practices, and the depletion of indigenous resources.

The totality of environmental degradation is problematic not least because of the inadequacies of the databases that are needed to assess, say, the effects of industrial emissions. For example, the US Toxics Release Inventory (TRI), the world's most comprehensive database of emissions, may underestimate the US emissions by as much as 10-fold! (WRI, 1994) while omitting to account for hazardous chemicals that become dissipated in products. Moreover, process-specific data often are not reported because of the diffidence in revealing proprietary information. Comparable difficulties arise when attempting to quantify the loss of biodiversity and rates of extinction (Myers, 1993a; Smith *et al.*, 1993). Within the European Union, substance flow analysis is being considered as a basis for developing financial instruments with which to address key environmental problems (Huppes *et al.*, 1992). Such analyses elicit economic and environmental flow, and accumulation statistics for selected substances and enable the main environmentally problematic flows to be traced back to source. The output of these flow analyses, which are determined on a transboundary basis, can be used not only for developing policy, but also in the investigation and specification of technical measures to reduce pollution. Turner and Powell (1993) make the telling point that, probably, the weakest link in environmental auditing is dose-response modelling and the construction of damage functions, i.e. the effects of pollutants on health and ecosystem demand much more systematic research. Recently, The World Bank has computed indices of pollution intensity (environmental risk from industrial emissions per unit of manufacturing activity) for each of 1500 industrial sectors or product categories. These indices relate to direct risk to humans, to aquatic organisms, to heavy metals, and to 'conventional pollutants' (WRI, 1994), and they have been used to provide some information on the environmental burden accumulating in a wide range and large number of countries.

This final point cycles the discussion back to the global commons and how we might avert the 'tragedy of the commons' which was re-articulated so explicitly more than 25 years ago by Garrett Hardin (Hardin, 1968). Recently, O'Riordan (1995) has directed our attention to two sets of commons whose management must be based on internationally agreed rules in order to protect global interests. These are 'international commons': systems outside the jurisdiction of individual nations (atmosphere, biodiversity), and 'shared resources': systems that cross international boundaries but which are geographically contained (ground water, regional seas, migratory animals). But with an undiminished sense of circumspection Hardin warns of the dangers of an *un*managed global commons in which low environmental standards drive out high ones. Hardin argues that, 'those who are really concerned with the environment – concerned with the well-being of posterity – must give the carrying capacity of the environment precedent over discontinuous human needs' (Hardin, 1994).

Environmental pollution: research and development perspectives

Pollution prevention frequently is viewed in terms of a hierarchy of management options, the principal ones of which are: reduction of waste at source; recycling of waste on-site within a manufacturing or other process; reusage of waste as a secondary feedstock for other (bio)technological processes; treatment of wastes either in-line, end-of-pipe or off-site when their prevention or recycle cannot be avoided; and, failing all other options, disposal (Bull, 1992). Early preoccupations with environmental problems tended to focus on the *symptoms* of such pollution rather than its *causes*, a perspective which provides the driving force for developing treatment technology while helping to direct attention away from long-term strategies required to bring about waste minimization. Throughout the past decade, the focus has gradually shifted such that the preferred options are prevention and recycling.

I turn first to aspects relating to treatment-cum-remediation and opine that successful developments are not likely to be seriously technology-limited (see Bradshaw *et al.*, 1992 for evidence). Rather the outstanding issues are of the following kinds:

(1) A lack of detailed knowledge of industrial manufacturing processes in order to assess their amenability to innovative biotreatment or bioprevention technologies, a situation which particularly frustrates much of academic research and development.
(2) The scarcity of demonstration or full-scale processes modified for in-line (up-the-pipe) treament of pollutants, i.e. add-on unit stages for cleaner technology (for example, the in-line biotreatment of toxic haloalcohols during paper chemicals manufacture, Bull and Hardman, 1995).
(3) The as yet wide lack of experience of *in situ* bioremediation of contaminated sites (soils, groundwaters, sediments) and reliable guidelines for recommending its adoption other than on a case-by-case basis.
(4) Establishing a consensus on appropriate criteria and data with which to define environment management strategies such as best practicable environmental option (BPEO) (O'Riordan, 1995). Rational decision making, however, is currently complicated by non-technical (i.e. social) and non-economic factors which have to be taken into account, by the scale and complexity of pollution problems, and by the plethora of potential technical remedies; and
(5) A determination to implement extant technologies.

More specific priorities for biotreatment research should address:

(a) The treatment of micropollutants and dispersed pollutants. These problems will be significantly more difficult and expensive to resolve than those contained pollutants that can be controlled by end-of-pipe treatment. The dispersion of heavy metals in sewage sludge, estuarine and marine sediments, chlorinated solvents in groundwater, and persistent estrogenic chemicals and mimics such as *p*-nonyl-phenols are illustrative of these classes of problem (ethinyl estrogen, for example, is an effective environmental hazard at $10\,\mathrm{pg\,l^{-1}}$).
(b) The development of robust (bio)sensors for rapid, on-line and *in situ* measurement and monitoring of environmental chemicals.
(c) The strengthening of ecotoxicology research with a sharper focus on the identification and measurement of damage-impact on ecosystems, and effects on human populations.
(d) Improved understanding and predictive behaviour of the physiology of detoxifying microorganisms particularly when growing in communities and attached to surfaces. Moreover, in very many cases the identity of organisms constituting competent biodegradative communities – whether operating in biotreatment reactors or *in situ* – simply are not known or their presence even recognized; under these circumstances rational design of remediation processes will be severely compromised. The recent study of xenobiotic-degrading β-*Proteobacteria* made by Busse *et al.* (1992) is

illustrative of the type of taxonomic work that needs to be done in this field; base-line data of this sort are so few that considerable investment of research effort will be necessary to enable unequivocal analyses of population dynamics and thence process control in biodegradation operations.

Further developments, such as the construction of taxon-specific, fluorochrome-tagged DNA probes, are opening up possibilities for identifying the physiological significance of different components of biodegradative communities. This latter approach is going to be crucially important for assessing the ecological significance of so-called 'viable but non-culturable' bacteria. Thus, the analysis of activated sludge bacteria with DNA probes for α-, β-, and γ-*Proteobacteria* has revealed that the β-group is discriminated against by current culture methodology and hence its contribution to ecosystem function could be seriously underestimated (Wagner *et al.*, 1993). While such DNA probing facilitates studies of population dynamics, even of non-culturable organisms, an additional challenge for the bacteriologist is to devise culture media for the enumeration of the β-group.

(e) Assessments of the efficacy, need and desirability of developing genetically modified organisms (GMOs) for contained and *in situ* biotreatment. Developments in pathway engineering notwithstanding, complementary research directed at the detection and isolation of natural microorganisms capable of metabolizing recalcitrant xenobiotic chemicals remains the most important priority for biotreatment technology.

Much in these research agendas is neither radically new in concept nor in technical detail. Nevertheless, the fact that such agendas have retained similar priorities for more than a decade (Bull, 1980, 1992; OECD, 1994) emphasizes the magnitude of the research tasks in this field and the need for continued attention to the science that underpins biotreatment and bioremediation technologies. In the remaining part of this section, however, I address one of the long-term requirements for enhancing environmental quality, namely, a greatly improved understanding of ecosystem function as an essential prelude to determining roles for biotechnology in ecosystem restoration. Nowhere is this more urgently needed than at the microbial level. Pardoxically, the supreme dependence of ecosystem function on microorganisms – manifest both in evolutionary and ecological time frames (Price, 1988) – is reflected neither in the inventory of microorganisms nor in the understanding of microbial ecology *per se*. The context here is the degradation of the global commons (*sensu* O'Riordan, 1995), a set of interconnected crises which present very different intellectual challenges and which demand innovative research perspectives.

The emergence of 'earth system science' (Mooney and Chapin, 1994) – those activities which seek to scale local information to regional and global dimensions in order to comprehend the functioning of Earth *per se* – has its origin in the need to predict response to global change. Initially concentrating on climate change, the earth system response has subsequently embraced changes resulting from patterns of land use, loss of biodiversity, and major perturbations to atmospheric gas composition. Information deriving from such studies will be crucial for effective and rational biotechnology inputs to problems as diverse as CO_2 accumulation and arid land reclamation. The case of biodiversity and ecosystem function is a pertinent one: whilst there is increasing concern that loss of biodiversity may threaten global homeostasis, there is no consensus on what relationships exist between diversity *per se* and ecosystem integrity. Unfortunately, the present knowledge base is so inadequate that hypotheses such as the airplane rivet analogy and species redundancy (Ehrlich, 1991) remain largely untested. It may be that species diversity affects ecosystem processes most critically when those ecosystems are responding to environmental change (stress) rather than when they are at steady state (Mooney and Chapin, 1994).

Similar uncertainty attends the concept of 'keystone' species – those that exert a disproportionate effect on the persistence (or activity) of all other species (Paine, 1969) – and how they might respond to major environmental changes and to the introduction of aliens, e.g. deliberately released GMOs. A more operational definition of keystone has been provided at a workshop of ecologists convened in Hawaii late in 1994: 'a species whose impacts on its community or ecosystem are large, and much larger than would be expected from its abundance' (Power and Mills, 1995). This definition differentiates between keystones and other strong interacting species whose effects can be ascribed to their dominance of ecosystem biomass. Almost no authenticated, quantitative data exist on microbial keystone species but it is not unreasonable to assume that nitrogen fixing bacteria, mycorrhizal fungi, and the marine prymnesophyte algae whose activities contribute to the marine carbon sink and to the albedo effect, are globally significant members of this biotic elite. As Simberloff (1991) has argued, the concept of keystone species 'provides guidance in predicting community and ecosystem effects' in the face of environmental challenges 'though the predictions will be qualitative and general, like the concept itself'. Nevertheless, this set of hypotheses does suggest an important research agenda for environmental biotechnology. The lively debate which has arisen over the merits of using 'ecosystem health' ('the ability to maintain desirable vital signs, to handle stress and to recover equilibrium after perturbations') as the concept for developing new ways of assessing and managing environmental resources (Shrader-Frechette, 1994), only emphasizes the extent of uncertainty that exists even within the scientific community.

Finally, I draw particular attention to the marine environment in the context of the global commons and the rapidly growing interest in marine biotechnology as a resource for innovative and clean products and processes. Thus, although environmental management predominantly has been concerned with land-based issues ('terracentrism'; Norse, 1993) I consider that increased R&D effort should be devoted to:

(a) the responses of pelagic and deep sea microbiota to types of environmental pollution additional to well-publicised oil spills (e.g. heavy metals, persistent halo-organics);
(b) how such pollution modifies marine ecosystem processes; and
(c) the development of (bio)remediation technologies for marine and estuarine ecosystems.

Technological imperatives

The links between industrial growth, disproportionate *per capita* consumption of natural resources and energy in the North and the South, and environmental degradation are incontrovertible, and political and fiscal instruments increasingly are being introduced in attempts to minimize the effects of unsustainable growth. Benton and Redclift (1994) state the position unambiguously: incorporate increased sustainability in goods and services through better environmental management and techniques such as Life Cycle Assessment

(LCA), or, be prepared to adopt radically different and much 'greener' forms of social life that could imply radical social structural change. The transition to a position of greatly increased environmental sustainability is both a technological and moral imperative. It will demand societal transitions (Speth, 1992) that are demographic (the transition to population stability *before* the world population doubles again); technological (the transition to new generations of environmentally benign technologies that go beyond the 'best available technology' mind set which has tended to entrench old (compromise) rather than encouraging new (net beneficial) technologies); economic (transition to a situation in which prices 'reflect the full environmental costs', subsidies for the consumption of forest resources or energy or the use of pesticides are removed, levying taxes on pollution and the use of virgin materials); social equity (transition to a greater sharing of economic and environmental resources); and institutional (the transition to different arrangements among and between governments, commercial enterprises and people and upon which all other transitions ultimately will be dependent).

In the more restricted terms of this paper I focus on technological imperatives and, in particular, identify two involving biotechnology which, I believe, are quintessential elements of sustainable development: clean or cleaner technology, and ecosystem restoration.

CLEAN(ER) TECHNOLOGY

An appropriate starting point for this discussion is Manzini's philosophy of 'ecodesign', the bringing together of what is technically possible and what is ecologically necessary (Manzini, 1990; Johansson, 1992) and embracing ecological redesign of extant goods and services, and ecological design of new, replacement goods and services. In both cases the objective is to improve, in terms of whole life-cycle and performance, the global efficiency and compatibility of goods and services, thereby highlighting environmental consciousness in design. Thus, it is cognizant of the fate of a product at the end of its life when recycling (preferably) or safe disposal (minimally) are essential requirements. Life cycle analysis provides a valuable conceptual approach to ecodesign, or green design as it is also termed. Life cycle analysis, or cradle-to-grave analysis, seeks to *quantify* the total environmental burden of processing raw materials and energy for the manufacture of a product *and* its subsequent distribution, use and disposal (WRI, 1994; Mackinson, 1995); it is concerned with the collection of data and the production of inventories. Life cycle assessment takes the analysis a stage further and attempts to *evaluate* and implement opportunities for effecting environmental improvement. Thus, during the design process – or even in the modification of an extant industrial operation – opportunities are identified for reducing environmental impact via: avoidance of contaminated ingredients and feedstocks and prevention of contaminated products; improving reaction stoichiometries and reducing toxic by-products; recycling materials and energy; minimizing effluents generated in cleaning operations; or extending the life span of a product. In short, life cycle assessment takes into account not only the particular manufacturing (or other) activity *per se*, but both upstream and downstream environmental contingencies, i.e. it embodies holistic principles and actions.

What is clean technology? It includes the development of cleaner products as replacements for polluting products, the introduction of waste-free (or minimal waste) processes, and the adoption of environmentally compatible practices irrespective of the economic or sectoral context. The epitome of clean technology is the systematic approach which it engenders in 'determining all the environmental impacts and resource depletions associated with providing (human) benefit or services' (Clift and Longley, 1995). There is an implicit recognition that biological processes, because they are natural processes, inherently provide cleaner options for both goods and services. The case for biotechnology innovations in the progress towards clean technology has been advocated recently by the OECD (OECD, 1994) and the desirability reinforced of clean process options over end-of-pipe treatment and bioremediation of polluted sites. Among the target sectors for biotechnology penetration should be included: (1) conventional industrial processes based on high temperature, highly reactive chemicals, extreme pH, and organic solvents; (2) agro-forestry practices based on xenobiotic chemicals; (3) foods and food processing; (4) raw material provision; and (5) mineral extraction and processing. Clean and cleaner biotechnology implementation is exemplified by the following activities:

(1) Industry

Significant progress has been made on the R&D of environmentally compatible functional materials like plastics and other polymers, fibres, surfactants, and adhesives either by exploiting direct biological analogues (bacterial polyhydroxyalkanoates, marine bacterial glycolipids), or mimicking natural products (mussel bysuss, spider silks). Bysuss, the L-dopa-rich protein attachment threads of mussels, is a water-resistant adhesive having extremely high log stability constants for metals and other materials; the natural product is commercially available and opportunities exist for producing chemical analogues (Waite, 1991). Spider silks can be produced as recombinant proteins with the ability to 'tailor make' silks with required properties (Kaplan *et al.*, 1991). Particularly interesting is the prospect of controlling the enantioselectivity of enzymes simply by altering the pressure of supercritical fluids (Kamat *et al.*, 1995). Under these circumstances enzyme activity and stereoselectivity might be manipulated in a predictable manner by changing just one process parameter – pressure – without the need to change the solvent system. Other interesting possibilities for clean products and processes might be found among biominerals; if the principles governing the biological control of mineral shape, texture, structure and assembly could be determined, a biomimetic approach to inorganic materials production might emerge (see Mann, 1995 for an assessment of potential options).

A major breakthrough in industrial processing, the potential of which was highlighted in the first OECD report on biotechnology (Bull *et al.*, 1982), has been the widespread introduction of biosynthesis, by either enzymes or by cells, for industrial scale catalysis. The list of examples, including commercial products based on enzyme technology, testifies to the technical and economic value of this biotechnological option: for example, acrylamide monomer for clean manufacture of polymers (Yamada and Nagasawa, 1990); chiral epoxides as versatile synthons for speciality chemicals such as β-blockers (Leake *et al.*, 1992). The importance of chirality to the pharmaceutical chemicals industry is paramount and was first highlighted by the thalidomide experience (the initially marketed product was a racemic mixture of (−) and (+) isomers and the (−) isomer proved to be teratogenic). This experience has driven the development of chemical syntheses based upon chiral synthons in order to produce clean, safe products.

Microbial and plant enzymes already have a proven record of introduction into the food and other industries such as tanning, and considerable additional opportunities are available in the event of more favourable economic incentives or stricter regulatory measures being imposed. Consider: (a) a more energy-sparing process for instant coffee production using galactomannanases to reduce viscosity and thereby enable greater removal of water from the solid prior to freeze or spray drying (Punte, 1992); (b) use of xylanses and peroxidases in pulp pre-bleaching as a means of reducing chlorine treatment. Developments on the compatibility of organic reaction media and biocatalysts, especially for enhancing biotransformations of poorly water soluble materials, are well established but more recently attention has turned to supercritical fluids. Such fluids promise advantages in terms of their high diffusivity, enhancement of reaction rates, low toxicity, ease of downstream processing and recyclability. A recent example of their efficacy is in the transesterification of methylmethacrylate with ethylhexanol to produce optical polymers (Kamat *et al.*, 1992). Reaction rates with *Candida* lipase were several fold higher in anhydrous sulphur hexafluoride compared to the reference solvent hexane.

The overall advantages of developing biotechnological routes to bulk chemicals – renewable feedstocks, energy-efficient processing, recyclable or biodegradable wastes – are well recognized but such technology is not yet commonly used because of the relatively low-cost (in part politically manipulated) economics of petroleum-based options. The challenge of developing economically viable biotechnology for chemicals has been evaluated comprehensively by the Federation of European Microbiology Societies (FEMS, 1995). Bioprocess engineering strategies appear to provide the best opportunities for maximizing product concentrations while genetic engineering strategies will be the key for improving product yields and for directing substrate flux distribution.

(2) Agro-forestry

Of the opportunities available in this sector plant protection is examined by way of illustration. The introduction of chemical herbicides and pesticides has revolutionized the past half century of agriculture, horticulture and forestry. However, the downside of this technology is evident as high resource-demanding production processes for hazardous compounds, high application rates, detrimental effects on target and non-target species, and chronic dispersed pollution by persistent chemicals. One response of manufacturers has been to introduce herbicide resistant traits (via conventional breeding and recombinant DNA technology) into crop plants. However, such an approach vitiates the notion of clean technology. Rather the effort should be directed at methods to deliver effective minimal dosages and not the gross excesses currently dispersed into the environment, i.e. cleaner technology focusing on selective delivery and not, in this case, on the production of the pesticide (Clift and Longley, 1995; Johnson, 1995).

Better targets for introducing resistances into plants are presented by pest insects and phytopathogenic microorganisms. Thus, the expression of *Bacillus thuringiensis* toxin and trypsin inhibitor genes has rapidly complemented the development of natural and genetically modified (enhanced) bioinsecticides. Another option for the control of insect pests is based on the specificity of pheromones. Here clean pest control technology can be combined with clean production technology of a highly selective agent. A case in point is provided by the production of the pheromone (+)-disparlure which is used to control the Gypsy Moth; the appropriate chiral synthon required for the synthesis of (+)-disparlure can be obtained by using lipases for catalysis of various of the synthetic steps (Fukusaki *et al.*, 1992).

(3) Food industry

The major environmental problems in this sector are considered to arise from the contamination of feedstocks and ingredients, the contamination of food products, waste generation, packaging, and cleaning operations; of these, only the cleaning problem is unique to the food industry (Fryer, 1995). To date the clean technology philosophy has made little impact on the food industry but environmental constraints are expected to become increasingly stringent and to make its introduction imperative (Hiranjan *et al.*, 1994).

(4) Raw materials and feedstocks

Harnessing photosynthesis is a means of generating industrial feedstocks and producing materials of industrial potential, and for driving other clean processes, e.g. water treatment. Targets in this sector include: biosynthesis of specific chemicals (defined starches, oils); fructan as a feedstock; feedstocks from autotrophic microorganisms; utilization of crop residues; and dispersed systems – exploitation of non-crop plants, especially for marginal land. Consider: (i) linseed (*Linum usitatissimum*) as a source of industrial grade fibre that may be developed as a replacement for asbestos in geotextiles, fibrocements, and speciality paper pulps; (ii) the cultivation of corriander for petroselinic acid, a feedstock for plastics and detergent manufacture, or, cloning of stearate desaturase into a major extant crop species such as oilseed rape to achieve the same end; (iii) the development of vegetable oil methyl ester from oilseed rape as a clean 'diesel' substitute – claims are made for its properties being similar to diesel and heating oil, its greatly reduced greenhouse gas contribution, that engine modification is unnecessary, and that oil cake and glycerol by-products may be used via animal feed and fermentation feedstock outlets (see Staat and Vallet, 1994); (iv) microbial hydrogen-based energy economy.

(5) Minerals extraction, separation and processing

Bioleaching is a well-established metals technology. Opportunities exist also to introduce biotechnology options for metal separations processes, e.g. Ga(III) recovery from highly alkaline aluminium extraction liquors (Gascoigne *et al.*, 1991). A third area for consideration is that of metal finishing. Thus solvent degreasing of metal surfaces prior to electroplating can be achieved by cleaner biotechnology using tensides (binary mixtures of non-ionic surfactants) and microorganisms – (the former solubilize oils, grease and other contaminants (which are biodegraded) and can be continually reused over an approximately 2-year period (Punte, 1992).

The materials sector is a singularly problematic one for clean technology. Major contamination accompanies metal winning and processing while many metals are incorporated into dissipative products (lubricants, pigments, biocides, etc.) wherein opportunities for recovery or reuse are low or non-existent. In order to close the materials cycle, Ayres (1992) proposes that it will be necessary to ban or discourage dissipative uses, to increase the efficiency of recycling irreplaceable materials, and to develop substitute materials, preferably by biotechnology.

ECOSYSTEM RESTORATION

Ecosystem restoration presents an enormous and diverse set of challenges to biotechnology, and remains a very uncertain area. We do not know, for example, if there are thresholds beyond which recovery will not be possible. Here I look briefly at the possibilities for restoring desertified and deforested ecosystems. According to the OECD (1994) 35% of the global land area is threatened by desertification. 'Desertization' is the consequence of disturbance by natural agents such as climatic, geomorphic and paleotectonic processes; when its effects are exacerbated by human activities such as overgrazing and poor agricultural practices, the process is referred to as 'desertification'. Although *in situ* bioremediation will affect relatively small scale environmental recovery from pollution, the problems introduced by desertification and deforestation are of an altogether different scale and require understanding of ecological processes in detailed and sophisticated terms. Short to mid-term, partial solutions to restoring ecosystems will likely be found in the development of xero and halo-tolerant plants. Successful examples of this approach are given by the development of crop species for arid lands (e.g. lesquerella, *Lesquerella fendleri*, which is being developed as a source of hydroxy fatty acids for industrial feedstocks); and for combined saline, alkaline and arid conditions (e.g. *Allenrolfea*).

The restoration of complete ecosystems is a longer term objective which has its reference in successional colonization and to which biotechnological intervention must be aware. Promising in this context is the exploitation of mycorrhizal fungi, either by managing mycorrhizal species that are present in the soil with a view to restoring an ecosystem; or, by mycorrhizal inoculant technology as a means of aiding the establishment and growth of plants during revegetation (Fig. 1). Inoculation is likely to be needed at sites that have never supported plant communities (e.g. mining wastes) or where the soil has suffered major insult (e.g. erosion, desertification, salination) resulting in the depauperation of natural mycorrhizal fungi. These root-associated fungi have a dramatic

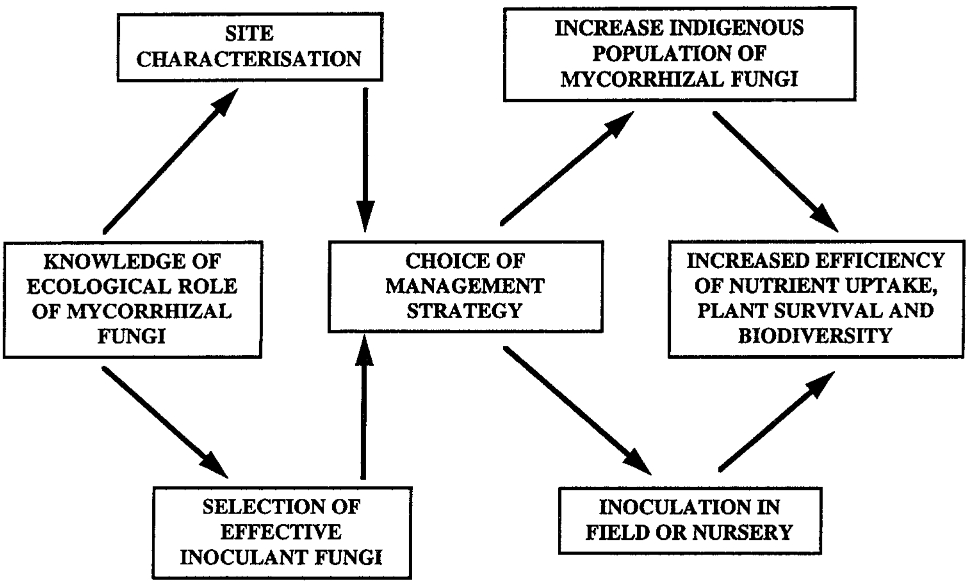

Figure 1. Planning criteria for the deployment of mycorrhizal fungi in reafforestation and revegetation. (Reproduced with kind permission of J.C. Dodd.)

capacity to redress various soil-mediated plant stresses – nutrient uptake, drought resistance, and protection against root pathogens (Sylvia and Williams, 1992; Jeffries and Barea, 1994). To date inocula of ectomycorrhizal species are amenable to fermentation production methods but their arbuscular mycorrhizal counterparts have to be produced at present by pot culture procedures. Given the ecological importance of these fungi as mediators of soil fertility and plant health, the R&D support is surprisingly meagre. Meanwhile, the necessary understanding of mycorrhizal succession, of the way in which mycorrhizal plants function as 'fertile islands', and of mycorrhizal fungal dynamics in soils and roots, including their association with nitrogen fixing bacteria, is rather slow to emerge. In addition to these considerations, it is becoming clear that mycorrhizal fungi interact with many types of soil organisms in a variety of ways.

From a practical point of view, mycorrhizal helper bacteria have been shown to improve the competitiveness of mycorrhizal inoculants in the presence of indigenous mycorrhizal species (Garbaye, 1991). Mycorrhizal associations, on the other hand, may promote disease resistance in plants but the present level of understanding is poor: for example, mycorrhizal susceptibility and disease susceptibility are known to be positively correlated in some cases thus making biocontrol applications unpredictable at present. As in other areas of biotechnology, short term empirical development of mycorrhizal inoculants for restorative purposes is likely to be thwarted, and is not a viable alternative to basic scientific intelligence.

Caveats

The significance of clean technology, and particularly biotechnology, for maintaining or even enhancing environmental quality notwithstanding, it is prudent to rehearse certain caveats lest the scenario is seen through too optimistic eyes (Bull *et al.*, 1982). Four such caveats I believe deserve brief consideration.

COSTS OF CLEAN TECHNOLOGY

In some commentators' minds there is an implicit belief that *bio*technology is clean. It is crucial to make comprehensive LCA of any purportive clean product or service that is being advocated via a biotechnology route as much as any other process technology. Consider the enzymes-in-food processing, and biodiesel examples discussed above. The intuitive confidence in enzyme-based processes as being clean, more efficient, and possibly even cheaper than competitive processes needs to be thoroughly examined by LCA, and include assessments of enzyme production (feedstock and energy requirements, fermentation conditions, preparation and purification, formulation, packaging) and conditions under which it is used. Similar arguments apply to biodiesel production and use: here the LCA would need to focus on the conversion process, the outlets for oil cake and glycerol by-products, land use (particularly set-aside as proposed in the European Union), pollution load (advantages are claimed regarding particulates and nitrogen oxides), comparative lubrication performance, and – by no means trivial given the proposed acreage of crop production in Europe – the widespread problem of allergenicity of rapeseed pollen. It should also be noted that the current unsubsidized cost of biodiesel fuels is approximately 2–5 times that of petrochemical products (Tao, 1994).

The incentive – or pressure – for industry to invest in clean technologies will be the result of various factors. Turner and Powell (1993) advance the following as some of the significant impediments to such investment: structural constraints (the need to amortize extant manufacturing plant and equipment), commercial constraints (difficulties of marketing new products and processes), cyclical constraints (market dynamics), and the present availability of appropriate and acceptable clean technologies. Undoubtedly government measures, particularly economic instruments and financial assistance, will be necessary to steer industry in the direction of clean technology. In the UK, as elsewhere, government encouragement also is becoming available through innovative research and development programmes, and the dissemination of technical information.

The pace of adopting clean technologies, however, is unlikely to be rapid or uniform. In overall terms, it has been calculated that the costs of reducing or stabilizing the global pollution load lies somewhere between 2% and 10% of the gross domestic products of countries such as the USA and Germany (O'Riordan, 1995). Such is the magnitude of the problem that The World Resources Institute (WRI, 1994) has concluded that only the urgent implementation of price mechanisms, the removal of subsidies that do not encourage sustainable use (e.g. poor irrigation, water, timber, hydroelectricity and coal production operations), and international agreements will affect such an improved state of the global commons.

THE ON-GOING NEED FOR CLEAN-UP TECHNOLOGY

There are no absolutely clean technologies *ipso facto* there will always be a requirement for efficient and innovative waste treatment technology. The replacement of chemical process technology by biotechnology, for example, will not even guarantee a reduction in waste but the waste will be more manageable in that it will be degradable and may be suitable for recycle or feeding a subsidiary process. The point made by Turner and Powell (1993) is a potent one, 'Sometimes it is more effective to install end-of-pipe purification because a more fundamental change in the production process is either too risky or impossible. Thus the promotion of clean technology ... should not necessarily neglect innovation in end-of-pipe measures' (Turner and Powell, 1993). Some experts, for example Roberts (1992), go further and argue that options for disposal should be considered objectively and not abandoned simply because of a history of bad performance. Such considerations lead to my third caveat, that of technologies with which biotechnology is in contention.

COMPETING TECHNOLOGIES

The competitiveness of biotechnology *vis-à-vis* other technologies based, for example, on altered chemistry or on engineering must be borne in mind when advocating biotechnological solutions to particular problems. Consider for example: (1) substitutes and replacements of environmentally incompatible commodity chemicals by environmentally compatible ones, e.g. replacement of methylene chloride by *N*-methyl-2-pyrrolidone (Mitchell, 1992); or, (2) the development of a clean, renewable, solar catalytic decontamination process for water (Zhang *et al.*, 1994). The latter technology which is based on photocatalytic generation of hydroxyl radicals, has been trialed at field scale with water contaminated with trichloroethylene, pentachlorophenol, and mixed aromatic compounds, with very promising results. The technology has also been used to remove and subsequently recover heavy metals, and for killing contaminating bacteria (thus obviating the need to use chlorine). The equipment is portable so that treatment can be done on-site, and preliminary costings indicate that they are comparable to existing technologies. Moreover, environmental contamination situations exist for which effective biotechnological solutions are either remote or unlikely options. The removal of toxic metals from soils is a case in point and here the emergence of electrochemical processes (electroremediation, electroreclamation) is showing some promise in field trials and field applications (Witt, 1995).

DILEMMAS AND PROBLEMS HAVING NO TECHNICAL SOLUTIONS

I think it worthwhile to revisit, albeit briefly, Garrett Hardin's class of human problems called 'no technical solution problems' (Hardin, 1968), reluctant as the scientist and technologist may be to admit such. Hardin's thesis was directed at the 'population problem' as one having no technical solution; the restoration of global environmental quality – the degradation of which is itself contributed to massively by the 'population problem' – presents us with similar difficulties. For the deep ecologist (Naess and Rothenberg, 1989) a sustainable environment is possible only through a radical change of consciousness in his/her relationship to the natural world. While most people might be more prepared to adhere to a 'shallow ecology' philosophy (accountable for environmental degradation, polluter-pays principle), we should be mindful of the diversity of public attitudes when extolling (over-extolling?) biotechnology or any other technology in this context. Thus, whereas biotechnological and chemical processes are being developed to use carbon dioxide as an industrial feedstock, for example, a chemicals and fuels industry based on CO_2 would account for less than 1% of the total annual emission of CO_2 (Magrini and Boron, 1994).

Finally, our need to face up to 'no technical solution problems' might be heightened by phenomena which Myers refers to as environmental synergies and environmental discontinuities (Myers, 1993b). Synergistic effects stem from the interactions of environmental processes such that the outcome (problem) is an amplification not merely an addition, a phenomenon illustrated by Myers with reference to ozone-layer depletion and global warming (here increased UV-B radiation might significantly disrupt the UV-sensitive marine phytoplankton CO_2 sink so that global warming is exacerbated). Environmental discontinuities present themselves when, for example, ecosystems which have absorbed long-term stresses without obvious signs of damage eventually reach a threshold at which point the cumulative environmental insult assumes critical proportions – the effects of acid rain on forestry losses.

Closing the circles

Implicit throughout this discussion is the conviction that the application of biotechnology for the enhancement of environmental quality, in its most comprehensive sense, demands an holistic approach based on the concepts of ecosystem ecology. This perspective differs from much of contemporary science – particle physics and molecular biology, for example – where the intellectual focus has become increasingly reductionist. Haber (1993) has argued that humans prefer linear thinking rather than network thinking. Ecological thinking and modelling, *ipso facto*, are conceptually difficult. Moreover, the situation is exacerbated by what Haber defines as the other preference in human thinking: simplistic interpretation (mechanistic causality) of phenomena. These matters take on importance when scientists and technologists are in dialogue with politicians or developers, for example, who insist on simple, synoptic explanations. Haber's rather pessimistic conclusion is that the environment 'is being spoiled by oversimplification of its complexity as much as by pollution and degradation'. In this section, I raise three issues that bear on environmental quality and illustrate the urgent need for the closing of circles if we are to affect solutions to problems resulting from an unmanaged global commons. These issues are: industrial ecology, biotechnology-biodiversity synergies, and North–South dilemmas.

INDUSTRIAL ECOLOGY

In the light of Haber's perspective, therefore, the advancement of the concept and practice of 'industrial ecology' is greatly encouraging. Traditionally, industrial processes have been structured as assemblies of unit stages frequently operating as if they were independent of each other and expending a once-through use of materials and energy. Frosch and Gallopoulos (1989, 1992), however, were amongst the first to stress the need to view such activities as an industrial ecosystem wherein 'each process and network of processes must be viewed as a dependent and interrelated part of a large whole', i.e. as mimicking their biological analogues, or, in Clift and Longley's (1995) terms denoting 'a relationship in which systems providing different services and products "metabolise" successive uses of material and energy'. And even though the ideal industrial ecosystem may not be achievable, the approach towards it is catalysing a major change in attitudes and practices. The precepts of industrial ecology perforce will encourage proaction rather than reaction, design-in rather than add-on, and flexibility rather than rigidity.

The analogy between biotic and industrial ecosystems and their respective evolution has been the subject of insightful scrutiny by Jelinski and her colleagues (Jelinski *et al.*, 1992). In their terms so-called 'type I ecology' displays linear material flow (unlimited resources + small population = no environmental impact) and might reflect the situation at the earliest stages of biological evolution on Earth, i.e. resources were so extensive and life forms so sparse that their existence had negligible impact on the resource base. 'Type II ecology' is based on interactive biological communities and limited proximal resources: it is quasi-cyclic. While it is more efficient than type I ecosystems it is not sustainable over long periods due to the condition that flows are unidirectional, i.e. the system ultimately runs down. Finally, within 'type III ecosystems', flows are almost completely cyclical (with the exception of the solar energy input) and resources and wastes are not differentiated in the fully integrated network – the system is sustainable. Jelinski *et al.* (1992) regard industrial ecology as having four central components or nodes which represent materials provision, materials processing/manufacture, consumption, and waste processing. The closer the operation of the nodes and the entire system approaches cyclic material flow, the more efficient and less detrimental impact they have on external support systems and the closer they approximate type III ecology.

Rarely, if ever, does recycling or reuse entail zero resource consumption and/or environmental pollution and the widespread introduction of quasi-industrial ecosystems is probably a long way off. However, a number of examples are available now that demonstrate the incorporation of the principal features of industrial ecology. Most examples are found in the heavy industrial sectors (e.g. metal conversions and refining, chemicals and petrochemicals) or where environmentally hazardous usage has been clearly authenticated (e.g. use of organic solvents, CFCs) (see Frosch and Gallopoulos, 1992; Jelinski *et al.*, 1992; Clift and Longley, 1995). Increasingly, however, the industrial ecology philosophy is penetrating other sectors such as the agriculture, food and pharmaceutical industries, and the supply and use of energy. Moreover, the Kalundborg experience demonstrates how industrial ecology can be implemented at a community level where the 'nodes' in Jelinski's model comprise farmers, pisciculture, a power plant, an oil refinery, a biotechnology company, a plasterboard factory, a cement works, and a domestic heating utility (WRI, 1994; Edgington, 1995). What is inescapable, in my judgement, is the necessity of an 'holistic approach' – which industrial ecology engenders – if a balance is to be achieved between narrow economic benefits and environmental quality. Further seminal discussion of this topic is provided by Ausubel (1992).

BIOTECHNOLOGY – BIODIVERSITY SYNERGIES

The second and third issues of concern in the context of global sustainability and environmental quality are closely related – biotechnology, and the North–South confrontation. There is an opinion, quite frequently expressed, that biotechnology

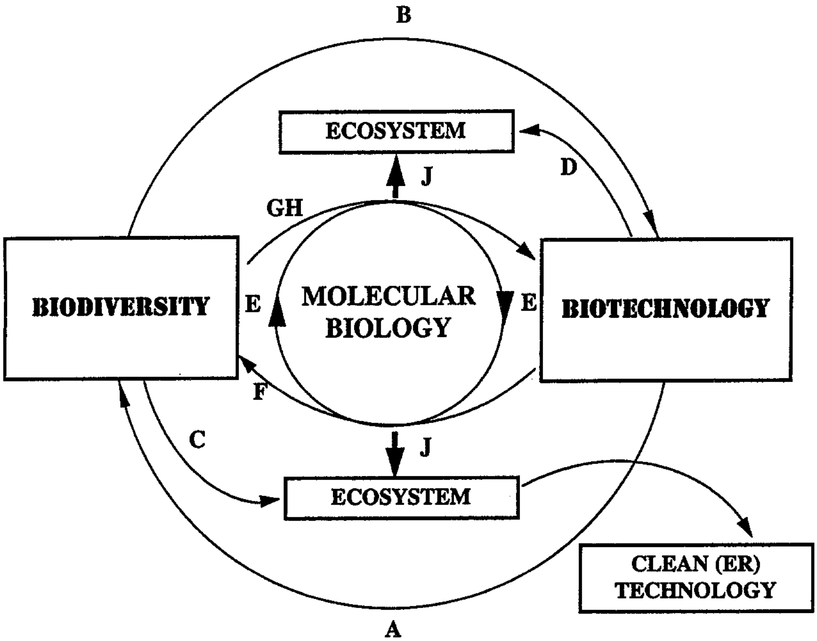

Figure 2. Biotechnology – biodiversity synergies: A, detection, circumscription and phylogeny; B, search and discovery; C, ecosystem function; D, bioremediation and ecosystem restoration; E, molecular biology gearing between biotechnology and biodiversity; F, definition of genetic (intraspecific) diversity; G, provision of tools for molecular biology; H, gene pools for recombinant DNA technology; J, genetically manipulated organisms for environmental biotechnology.

innovation is incompatible with biodiversity conservation. Shiva (1993), for example, declaims that, 'There is a prevalent misconception that biotechnology development will automatically lead to biodiversity conservation. The main problem with viewing biotechnology as a miracle solution to the biodiversity crisis is related to the fact that biotechnologies are, in essence, technologies for the breeding of uniformity in plants and animals'. Regrettably this is a gross distortion of the definitions of biotechnology that had been proposed and accepted a decade or more earlier (Bull *et al.*, 1982) and none of which adopted such a narrowly proscribed position. On the contrary, as the biotechnology sector has matured the biotechnology–biodiversity circle has been closed by a number of mutually beneficial flows of materials, services and ideas. The following are prominent among these interactions.

(i) Detection, circumscription and phylogeny of biological diversity (Fig. 2 [A]). The recent spectacular developments in this field have been made possible by those in molecular biology which, in turn, have been catalysed largely by the demands of biotechnology. The comparison of small subunit ribosomal (ss rRNA) sequences has led to a major reappraisal of the living world and its delineation into three supra taxa, the Domains (Woese *et al.*, 1990), while the construction of specific DNA probes has enabled searches to be made for particular genes in any taxa of interest. The application of molecular biological techniques has had a signal impact on bacteriology and notably on problems such as species definition, and non-culturability that have long hampered progress. Thus the availability of molecular tools allows direct analysis of environmental ss rRNA, and thence phylogenetic attributions, to be made without the necessity of culturing the organisms *per se.* In other taxa, for example the green algae (McCourt, 1995), molecular analyses also have raised major questions about the validity of using phenotypic characters such as morphology as overriding criteria in classification.

Considerable uncertainty attends the question of the rooting of the phylogenetic tree and whether or not the Archaea is monophyletic. Recent work based on ancient aminoacyl-tRNA synthetase genes (Brown and Doolittle, 1995) provides further support for the hypothesis that the Archaea and Eucarya are sister groups, and for the monophyly of the Archaea. Nevertheless, the equivocal evidence coming from the analysis of other ancient duplicated gene families (ss rRNA, ATPases, elongation factors) cautions that, at this juncture, our understanding of evolutionary relationships remains very incomplete.

(ii) Search and discovery (Fig. 2 [B]). Natural biodiversity provides the major material for biotechnological innovation: it is the planet's greatest but least developed resource (Wilson, 1988). The recent development of mode-of-action, enzyme inhibitor, and receptor agonist/antagonist screens, and various other targeted screening procedures has led to the discovery of numerous antibiotic, biopharmaceutin, biocatalytic, and biocontrol products, and novel biomaterials, to mention but a few biotechnological discoveries (Bull *et al.*, 1992). Biotechnology search and discovery embraces the whole range of biodiversity, recent exploitable products and properties having been developed from microorganisms, angiosperms, gymnosperms, invertebrates (molluscs, arachnids, polychaetes), and many other taxa.

This direct biotechnological value of biodiversity is obvious; less obvious are the implications for biodiversity – particularly microbial diversity – conservation. On the one hand *ex situ* culture collections are very unlikely to be able to house more than a small percentage of the estimated numbers of microorganisms (and even less of their intraspecific genetic diversity; see below) while on the other hand, the properties of many microorganisms when kept in such collections are altered or lost completely, thereby compromising their biotechnological utility. Consequently, microbiologists should participate much more aggressively in conservation planning and management. Special consideration needs to be given to ecosystems which are dominated by or strongly influenced and stabilized by microbial activities (Trüper, 1992). These ecosystems will include cold and hot deserts, hypersaline and alkaline soils and lakes, geothermal environments (marine, terrestrial), deep oceans, and wetlands including marshes, swamps, mangroves and stromatolite communities. It is arguable that selected (but carefully managed) polluted sites also should be gazetted as hot spots of evolutionary activity vis-à-vis the transformation of xenobiotic chemicals.

(iii) Ecosystem function (Fig. 2 [C]). The functioning of all ecosystems depends ultimately on microorganisms and, as Hawksworth (1994) has argued, microorganisms are crucial for maintaining all other life whether at an individual, ecosystem or global scale. It is ironic, therefore, that comprehensive studies of the roles played by microorganisms in ecosystem function and homeostasis have been so neglected. The technical difficulties of studying microorganisms are, in part, responsible for this situation but more complete understanding will result only from a closer integration of microbial and macrobial ecology, and greater drawing of attention to microorganisms in discussions of biodiversity and conservation issues (for example, see International Committee on Microbial Diversity, 1994). From a practical viewpoint, investigations have been made more tractable as a result of molecular techniques. Thus, while the concept of functional groups of microorganisms has proved useful and is likely to persist, molecular techniques enable individual taxa and their contributions to ecosystem function to be identified, and even offer the possibility of defining microbial keystone species. Such possibilities for analysis also exist now at the global scale. For example, the unexpectedly high abundance of pelagic marine archaea recently revealed by the use of rRNA probes (DeLong *et al.*, 1994) may be a critical observation in this context. The abundance of these prokaryotes in Antarctic seas, compared to other marine picoplankton communities, and the fact that cold seas comprise one of the largest biomes on Earth, argues that such archaea represent a major component of the marine biota and probably contribute to globally significant biogeochemical processes. Finally, and in the longer term, improved understanding of ecosystem functioning may further influence trends in industrial technology and promote further adoption of clean processes and products.

(iv) Bioremediation and biorestoration (Fig. 2 [D]). Bioremediation invokes the use of biological diversity to reclaim habitats that have been contaminated by hazardous materials. It shares with biorestoration the objective of stimulating the activities of indigenous organisms, or the introduction of extrinsic organisms, to effect *in situ* detoxification, mineralization or bioremoval of pollutants. Bioremediation processes more frequently are based on the activities of communities of microorganisms and such communities may have to be selected to cope with one or more specific chemicals, toxic materials, mixed pollutants, and very low (chronic) concentrations of pollutants. Again, because of the complexity of such polluted habitats, empirical intervention is very unlikely to produce successful bioremediation processes; the management considerations outlined in Fig. 1 are as applicable to bioremediation as they are to reafforestation and revegetation operations.

(v) Molecular biology – the gearing between biotechnology and biodiversity (Fig. 2 [E]). Molecular biology has had a dramatic impact both on the development of biotechnology and on the exploration and definition of biodiversity, moreover it provides much of the gearing between the two areas. Biodiversity provides an extraordinarily large and rich gene pool for recombinant DNA technology (Fig. 2 [H]) which, in turn, is the driver for much of contemporary biotechnology. 'Gene technologies stand among the ultimate beneficiaries of the vast library of tried-and-true evolutionary inventions of the millions of species in natural ecosystems and thus have an interest in keeping these libraries in viable condition' (Colwell, 1994). I will refer here to three facets of this interaction: genetic diversity, tools for molecular biology, and genetically manipulated organisms (GMOs) for environmental biotechnology.

(vi) Genetic diversity (Fig. 2 [F]). The advent of molecular techniques has revealed the considerable extent of genetic (*sensu* intraspecific) diversity. Access to this type of information has consequences for conservation (*in situ* versus *ex situ*), biogeographic studies, and search and discovery projects. In the latter context, the ability to correlate molecular characteristics, such as restriction fragment length polymorphism, with sought biotechnological properties opens the way to rapid, targeted screening in which only those taxa most likely to possess the required property are included. The assessment of strains of *Lactobacillus plantarum* for development as silage inoculants (Bull *et al.*, 1992), the identity of strains of *Trichoderma harzianum* that are aggressive colonizers of mushroom compost (Muthumeenakshi *et al.*, 1994), and the differentiation of mosquito pathogenic and non-pathogenic strains of *Bacillus sphericus* (Woodburn *et al.*, 1995) illustrate the uses to which such analyses can be put.

(vii) Tools for molecular biology (Fig. 2 [G]). Biodiversity and particularly microbial diversity provide the tools for modern genetic manipulation. In order to illustrate this point, consider the polymerase chain reaction (PCR) a procedure now used universally to amplify DNA *in vitro*. The DNA polymerase from the thermophilic bacterium *Thermus aquaticus* is used in PCR because its thermostability enables it to be recycled without it being denatured by the high temperature required to separate the DNA strands. However, alternatives to this *Taq* polymerase are being sought that have more desirable attributes, e.g. proof-reading function, improved fidelity and thermostability. Thus among the new generation of DNA polymerases are those from archaea such as *Pyrococcus* and *Thermococcus* that have such enhanced properties.

(viii) Genetically manipulated organisms (GMOs) for environmental biotechnology (Fig. 2 [J]). The consensus of the scientific community has moved towards the view that GMOs can be used safely and efficiently for bioremediation. Timmis *et al.* (1994) consider that there are four bioremediation targets for genetic engineering. The first, which is relatively trivial, is the quantitative improvement of catalyst performance. Pollutant degradation may be rate-limited as a consequence of catalytic activity and/or catabolic regulation and in either case improvements can be achieved by genetic manipulation. Secondly, the stability of bioremediating microorganisms may be improved by engineering the amino acid sequences of key but unstable enzymes; and their substrate range widened by modifying enzyme active sites. For example, the P450-cam of *Pseudomonas putida* is capable of dehalogenating hexachloroethane but not 1,1,1-trichloroethane (Logan *et al.*, 1993). Site-directed mutagenesis or other manipulations may so alter the topography of the enzyme active site that it can accommodate the trichloroethane and hence affect its dehalogenation. Thirdly, metabolic pathway engineering to enable individual species to bring about the complete degradation or detoxification of pollutant chemicals, e.g., combination of polychlorinated biphenyl (PCB) and chlorobenzoate catabolic activities in order to alleviate the accumulation of inhibitory chloroaromatics by PCB-transforming bacteria. Fourthly, and most significantly, are the opportunities to engineer degradative organisms for improved performance under *in situ* bioremediation circumstances. Such modifications may relate to stress resistance (e.g. heavy metals or high salinity), the ability to adhere to particles or, conversely, to migrate through substrata, and the incorporation of reporter genes (e.g. bioluminescence) for *in situ* monitoring of biodegradation. Innovative genetic manipulation is not a replacement for the management of natural biodiversity in bioremediation. Microbial consortia, for example, will prove to be more robust, more cost effective to develop, or more acceptable than GMOs in many circumstances. Adoption of these alternative strategies will be determined by many considerations and the nature of the particular environmental pollution problem. Finally, to those who opine that genetic manipulations might extend the pool of biodiversity the remark of Robert Colwell is relevant: 'In whatever measure this ambitious prediction comes true, the implication that laboratory art can truly imitate life betrays a narrowly reductionist view of adaptation and evolution' (Colwell, 1994).

Unfortunately, this cirle of biotechnology-biodiversity interactions contains some potentially non-sustainable elements, the massive habitat distortion for biotechnology feedstock crops being one of the most evident. The planting of genetic monocultures has eroded the genetic diversity of most major food crops and reduced the spectrum of cultivated species (Colwell, 1994). This trend is likely to continue: consider crops such as soybean and oilseed rape as industrial feedstocks (the plans of three EU countries alone are to commit over two million acres of land for biodiesel production). A second downside to such developments is the potential for increased genetic vulnerability to pathogens and pests.

NORTH–SOUTH DILEMMAS

The third, and possibly the most critical impact of biotechnology in this context could be the long-term displacement of agricultural export commodities from the Third World, a scenario which was sketched in the OECD's first report on biotechnology (Bull *et al.*, 1982). While this is not the place to discuss North–South issues in detail, there is a sub-set of issues which undoubtedly impact on the theme of this paper. In particular, consideration must continue to be focused on the facts that mega-diversity countries are mainly of the South while the principal commercial exploiters of biodiversity for biotechnology are in the North; and the intellectual property rights and protection of biodiversity and indigenous peoples of the South. The latter, hotly debated in Rio during the UNCED Conference, has come under further challenge in consequence of provisions drafted at the Uruguay round of the GATT. Shiva (1993) and Reid *et al.* (1993) provide extensive treatment of such North–South issues affecting biodiversity and biotechnology.

Final thoughts

Paul Kennedy in his book, *Preparing for the Twenty-first Century* (Kennedy, 1993), asks in the context of monitoring the pace and complexity of change, 'is *any* social group really "prepared" for the twenty-first century? ... even technologically better-prepared countries face difficulties in dealing with certain forces for global change: the decline in fertility rates; population imbalances; global warming; financial volatility; the need to cushion farming communities from increasing obsolescence'. This scale problem is echoed by Haber (1993) who draws the contrast between the time-scale of most people (i.e. an adult life-span of 40–50 years) and the time-scale relevant for environmental problem solving (i.e. a political time scale of 4–5 years). Thus, a sense of stewardship is a vital ethical imperative for our times. Based on the Land Ethic principles of Aldo Leopold ('A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise'), the emergence of environmental ethics came about in the 1980s at the instigation of Japan (Berry, 1992; Sylvan and Bennett, 1994) and at the first bioethics conference in Brussels in 1989 the need for an Environmental Code of Practice was enunciated and agreed. The Code is based on the ethic:

> 'stewardship of the living and non-living systems of the earth to maintain their sustainability for present and future, allowing development with equity.'

It is prudent, therefore, to adopt the 'principle of precaution' (O'Riordan, 1995) for the environmental perspective as we approach the millennium – thoughtful action in advance of scientific verification of cause and effect, care in management, placing the burden of proof on the developer, and *leaving ecological space as room for ignorance.* 'The future value of biodiversity ... can only increase ... As long as the perverse alchemy of non-sustainable exploitation of biological resources continues to turn gold into lead, those who sustain the diversity of living things and their genetic inventions will find themselves custodians of a treasure trove of ever-increasing worth' (Colwell, 1994).

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