PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

The Quantification of Biodiversity: An Esoteric Quest or a Vital Component of Sustainable Development?

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The quantification of biodiversity: an esoteric quest or a vital component of sustainable development?

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CONTENTS

SUMMARY

Biodiversity relates to sustainable development through a series of direct and indirect uses. These include direct harvest, nature tourism, wild genes improving domestic crops, wild species contributing to crop productivity, pest management, sources of medicine and bioremediation (biologically based environmental clean-up). Biodiversity relates through services, individual species indicating environmental change or stress, insights into the life sciences and increasingly today, through wealth generated from biodiversity at the level of the molecule. Sustainable development relates to the quantification of biodiversity through organizing information to enable the foregoing activities. It also relates in little-explored ways to ecosystem function, stability and resilience. Biodiversity is already a proven indicator of environmental change in freshwater systems.

1. INTRODUCTION

Accelerating extinction rates and the *Convention on Biological Diversity* have cast a new spotlight on studies of biodiversity and therefore, relevant research (Smith *et al.* 1993). Simultaneously, the scientific community has developed new interests in exploring and quantifying biodiversity. Wilson (1985) has called for a complete inventory of biological diversity and has recognized that learning how many forms of life inhabit the planet is a legitimate scientific quest. Similarly, Janzen (1993) has set forth the goal of an All Taxon Biodiversity Inventory (ATBI) to quantify and describe biological diversity in a discrete unit of landscape. These are certainly valid scientific goals of great relevance to evolutionary, ecological and biogeographical science, but do they or how do they relate to the current environmental and social imperative of sustainable development?

Sustainable development is far from tightly defined and we are far from a rigorous recipe of how to recognize it when we see it. Nonetheless, it is generally agreed that it must include maintenance of ecological systems, natural resource bases, and social structures and systems. This understanding is certainly sufficient to ask whether the new-found interest in quantifying biodiversity is some esoteric quest or whether it indeed relates in fundamental ways to sustainable development.

One obvious way that quantifying biodiversity relates to the societal imperative of sustainable development is that it includes straight forward biological good housekeeping, that is, the inventory, survey and monitoring of basic biological resources. This is the basic motivation behind the recent establishment of the National Biological Survey in the United States and the general recommendation emanating from the United Nations Conference on Environment and Development (UNCED) for the institution of biological surveys in all nations.

To most people, however, biological survey and monitoring seems an abstruse scientific activity concerned with a vast variety of weirdly named species about which no one has heard and which are of little relevance to human society. Unfortunately, the majority of human society is ignorant of the extent to which we depend on or benefit from a great array of other forms of life. Although such people might be willing to acknowledge that as living entities people need biological resources, most labour under the illusion that all that really matters is a handful of plant and animal species used as foods enlivened by a few more used as spices, with a couple of domestic animals such as dogs or cats thrown in for amusement.

2. ECONOMIC CONSIDERATIONS

In contrast, biological resources represent a significant contribution to economic activity and – provided they are managed prudently – therefore to sustainable development. Prescott-Allen & Prescott-Allen (1986) produced the first analysis of the importance of wild species to the United States economy. For the period 1976–1980 they estimated that 4.5% of the Gross Domestic Product (GDP) was attributable to wild species. Of this, 91% consisted of wild harvested resources (27 billion dollars or 4.1% of GDP), 7% was of wild resources in support of agriculture and 2% represented wildlife-based recreation. Their analysis of the living resource base showed 17% to be wild resources and a further 5% composed of new domesticates, wild genetic resources and the contribution of wild pollinators. In less developed nations, the wild element in economic productivity probably looms larger, although in many instances it is likely to occur unmeasured by the formal economy (IUCN 1993).

A recognition of the value of wild species to economic activity is inherent in the experimentation with extractive reserves in tropical forest countries like Brasil. In Brasil, such experimentation is largely focused on Brasil nuts and wild rubber. In addition, however, the *Babassu* palm forests of Amazonia hold considerable promise as extractive reserves (Anderson *et al.* 1991) which is not surprising given the high economic importance of the palm family in general. In southeast Asia, the various wild species of the climbing palms known as rattans are an important forest product. Indonesia's 1985 exports of unworked rattan was valued at $97 million. World trade in rattan products that year was estimated at $2.7 billion (Kiew 1991*a*; Mogea 1991; Pearce 1991).

Prior to the establishment of tropical areas specifically as extractive reserves, Peters *et. al.* (1989) conducted a provocative analysis of the economic potential of various extraction products from Amazonian forests in contrast to the yield from forests converted to cattle pasture. They demonstrated that extractive activity was potentially far more lucrative, but what was lacking was any way to estimate the market and therefore the price stability for the products. A somewhat similar analysis has been made of the economic value of traditional medicines from two forest areas of Belize (Balick & Mendelsohn 1992). For such schemes to become more than isolated examples, there is a need to develop means of transport of products which in turn do not attract destructive development. Nonetheless, non-timber forest products already play a significant role in informal and formal economies (Plotkin & Famolare 1992). This is true but probably to a lesser extent in industrialized countries such as the United States (Lipske 1994).

Another development in the contribution of biodiversity to economic development in recent years has been nature tourism (Boo 1990). In certain countries like Kenya and Costa Rica, nature-oriented tourism vies for place as the number one foreign exchange earner. Ecotourism seems to be developing rapidly in a large number of countries. Twenty-nine million United States citizens participated in a total of 310 million nature trips in 1980. Of these citizens, 1 031 000 made 4 067 000 trips to foreign countries. (U.S. Fish & Wildlife Service 1982) It is still difficult to get an accurate estimate as to the extent of world ecotourism but it is certainly on the order of billions of dollars annually (Lindberg 1991).

By themselves, extractive reserves and ecotourism would seem to be relatively weak arguments for the importance of biodiversity and its quantification to sustainable development. Indeed ecotourism can often unfairly be given an elitist cast. It is important to note, however, that the same wild areas of value for those economic uses can serve as resource reserves for other, often very sophisticated, economic uses of biodiversity.

3. AGRICULTURE AND PEST MANAGEMENT

Among the uses of biodiversity for economic activity which ordinarily escape mainstream economic calculus, is the use of genetic traits from wild relatives of domestic crop species. The international centres for various crops such as rice or wheat are continually turning to wild relatives for disease and pest resistance. Similarly, that part of the forestry industry which is actively engaged in reforestation and plantation forestry is continually drawing on wild genes to improve varieties. This use of wild genetic resources extends beyond wild relatives of crop or tree species to other species of great value to production such as nitrogen-fixing bacteria or mycorhizzal fungi. Relatively small increases in productivity or resistance to pests and disease can yield large increments in profitability.

Yet another way in which biodiversity contributes to economic activity is in integrated pest management to foster the more judicious use of pesticides. For example, two fungi, *Metarhizium flavoviride* and *Beauveria bassiana*, are currently proving effective in field testing against migratory locusts and agriculturally problematical grasshoppers (Leary 1994). This is not confined to agriculture and forestry but to other areas of resource management as well. Two species of *Opuntia* cactus had once spread in such density across an area of Australia equivalent to the size of the United Kingdom that half that area was rendered useless. Introduction of the moth, *Cactoblastis cactorum*, in 1925 eliminated cactus infestation from vast areas and has controlled it subsequently (Waterhouse 1991).

Similar examples of pest control occur all the time. The new volumes on the weevils of Australia might seem the ultimate in esoterica to some, and who, one might ask, has ever heard of a 'good' weevil? Yet these volumes (Zimmerman 1991) contain accounts of Lake Moondara, Queensland and the river at Imbuando Village, East Sepik, Papua New Guinea. There, choking mats of the Brazilian waterweed *Salvia molesta* once virtually suffocated the natural productivity and value for fish production of these fresh water ecosystems. Introduced Brazilian *Cyrtobagous* weevils led to the virtual elimination of the exotic plant and subsequently, the waterbodies have recovered. In a partial echo, another weevil, *Euhrychiopsis lecontei*, once a pest of an indigenous aquatic plant, mutated to a form which effectively attacks Eurasian water milfoil, *Myriophyllum spicatum*, which has become a serious problem species in the United States (Sheldon 1993).

4. PHARMACEUTICALS

In addition, unbeknown to most, wild species have been a vitally important source of medicines at least since Hippocrates was prescribing infusions of willow bark (the precursor of aspirin) as an analgesic. In the United States, it is estimated that 25% of prescriptions have active ingredients with plant origin. Sales of these have been estimated at 4.5 billion dollars in 1980 and 15.5 billion dollars in 1990 (P. P. Principe, unpublished data). In the United States, Canada, Europe, Japan and Australia, prescription and non-prescription drugs of plant origin were estimated to have a market value in 1985 of 43 billion dollars (Principe 1989). What is not included in these estimates is the economic activity generated by a healthier populace.

One of the more promising discoveries in recent years has been taxol which was initially isolated from the Pacific yew tree (*Taxus brevifolia*). It is being used in the treatment of ovarian and breast cancers. The vine, *Ancistrocladus korupensis*, first collected from Korup National Park in Cameroon, yielded the compound michellamine B, so successful in protecting human cells from the HIV virus *in vitro* that it is the first natural compound to move to animal testing for AIDS research (Washington Post 1994; Stix 1993). Squalamine, an aminosterol from the dogfish (*Squalus acanthias*), displays antiparasitic, antifungal, antiprotozoan and antibacterial activity, including against *Streptococcus*, *in vitro* (Moore *et al.* 1993). An Ecuadorian arrow poison frog, *Epipedobates tricolor*, secretes a compound which blocks pain 200 times as effectively as morphine but is not an opioid (Daly 1994; Spande *et al.* 1992).

Very often production of a pharmaceutical product initially requires a lot of material harvested in nature to extract the active ingredient but this is often superseded by the ability to synthesize. Although this means that in one sense the biological source is no longer necessary, it is important to recognize that it derives from the original inspiration, that is, the template provided by a wild species.

While it is possible the day may come when computers can be used to design molecules to affect particular disease organisms, even at such a time biodiversity will represent a pool of biologically active molecules pretested in nature which can be of immense value. For some time it has been thought that the odds of a potential lead in screening extracts from wild species for potential medical activity of one sort or another are but one in 10 000 (McChesney 1992). That coupled with the long lag times needed to translate a lead into a commercially successful medicine leads to highly discounted present value (Reid *et al.* 1993). The numbers seem to be changing in favour of increasing present value as screening techniques improve, and particularly with simultaneous screening for multiple types of activity. Prospecting for nature's biochemical riches (Eisner 1990) seems to be growing in importance.

5. ENVIRONMENTAL APPLICATIONS

The value of biodiversity to waste management and environmental clean-up problems, through a technique known as bioremediation, is increasing rapidly. The discovery of microorganisms with odd metabolisms and appetites can greatly facilitate solving such problems. One of the more intriguing is the bacterium found in the sediments of the Potomac river which has the ability to break down the ozone destroying chemicals known as chlorofluorocarbons (CFCs) (Lovley & Woodward 1992). Already there are commercial applications of microbes which break down organic molecules such as occur in oil spills. The major economic potential of bioremediation may lie in removing certain elements from waste streams before release from a factory.

6. MOLECULE-LEVEL BENEFITS

I believe we are in transition to an era when major benefits will accrue to human society and sustainable development from wild resources because of wealth generated at the level of the molecule (Bull *et al.* 1992). A new bioflocculant derived from *Strychnos potatorum*, a tree in Andrha Pradesh, appears to be able to clean up uranium and other long-lived isotopes of nuclear wastes. It appears to have similar ability to remove heavy metals such as cadmium and mercury from effluent (Jayaraman 1993). Azadirachtin from the neem tree (*Azadirachta indica*) from India has recently become a commercially available insecticide (Stone 1993). Marine organisms contain substances under investigation for various uses: discodermolide from a Bahamian sponge, *Discodermia* sp., may be useful in suppressing organ rejection after transplant operations; macrolactins from the Bahamas sea floor mud bacteria appear promising in inhibiting growth of melanoma and colon cancer cells as well as the herpes simplex and HIV (Fenical 1989, 1993).

Genetic engineering now makes it possible to introduce desirable genetic traits from one species into another which is not closely related. Pest resistant genes from *Bacillus thuringiensis* have been transferred to a variety of crop species (Gasser & Fraley 1992). A freeze-resistant strain of tobacco has been produced by inclusion of a gene from winter flounder (Gladwell 1990). The development of the 'Flavr Savr' tomato about which there has been so much controversy in the United States actually involves only the manipulation of tomato genes to delay the softening which normally comes with ripening so that ripe tomatoes can be shipped long distances without rapid spoiling (Singer 1993). There has been considerable trepidation about genetically engineered organisms among the public. Once it is better understood that, like most technologies, genetic engineering is essentially neutral and that benefits or problems relate instead to how the technology is applied, there should be rapid economic return generated from biodiversity in this fashion.

Probably, the most significant example of the power of a single molecule from the wild to generate new possibilities and economic development involves the polymerase chain reaction for the discovery of which Kary B. Mullis shared the 1993 Nobel Prize in chemistry. This reaction, which permits multiplication of DNA billions of times in a few hours, is now fundamental to diagnostic medicine as well as much of biotechnology. It depends on a heat-resistant enzyme discovered by Thomas Brock in the bacterium *Thermus aquaticus* which occurs naturally in hot springs in Yellowstone National Park (Mullis 1990).

The reaction, which is so basic in molecular biology as to be referred to generally as PCR, relates to probably the most important and least recognized relationship between biodiversity and sustainable development, namely the value of wild species as intellectual resources. Biodiversity in essence represents the most fundamental library in support of the life sciences: tens of millions of species with unique sets of properties, processes and 'solutions' to unique sets of biological histories and challenges. These are not, of course the only 'solutions', they are the ones which have evolved and survived to this moment. Many others have occurred in the past and the number which might evolve in the future is inestimable. Yet those currently existing tell us interesting things about how evolution has worked and can work. The discovery of the hydrothermal vent communities in the 1970s, which demonstrated that entire communities could depend on the primal energy of the Earth rather than solar radiation and that organisms could exist at temperatures greater than the boiling point of water, demonstrate just how far we are from understanding even the most basic dimensions of life on Earth.

7. SUSTAINABLE DEVELOPMENT AND ENVIRONMENTAL MANAGEMENT

The notion that biologically based development constitutes an important segment of sustainable development because of the ability of biological resources to renew themselves, supports the importance of the life sciences and the potential that can be derived from examining things that occur in nature. The power of concepts derived from observing nature to benefit society is exemplified by vaccination and *Vaccinia* (cow pox) virus and by antibiotics and *Penicillium* mould. Humanity's stake in being able to understand evolution is presumably more than a trivial and esoteric matter.

The properties that collectively make each species a vast store of information (Wilson 1985) also make them the most sensitive indicators of environmental change. The concentration of chlorinated hydrocarbons as these molecules passed up foodchains culminated in drastic declines of top predators such as peregrine falcons (*Falco peregrinus*) making them the first indicators of the 'Silent Spring' problems predicted by Rachel Carson. The toxic effects on non-target species such as the European oyster (*Ostrea edulis*) led to re-evaluation of the use and regulation of tributyl tin as an antifouling agent for nautical paints and coatings. Unhealthy and dying red spruce (*Picea rubens*) were the first visible indicator of the acid rain problem in North America.

8. ECOSYSTEM FUNCTION

Another argument often advanced about the value of biodiversity concerns the public services performed by the natural aggregations of biodiversity known as ecosystems. There is no question that the summed metabolism of the planet is conducted by the summed biodiversity and biomass, or that ecosystems play important roles in the cycling of nutrients, water, energy and biogeochemical cycling in general. When it comes down to specifics of the relationship between biodiversity and the functioning of ecosystems, the picture is far more complex and only fractionally understood (Schulze & Mooney 1993). For example, watershed regulation might seem provided as well by a plantation forest as by a highly diverse natural one.

Agricultural ecosystems drastically simplified for the pragmatic purposes of production, suggest at least a modest link between biodiversity and ecosystem function. Five different treatments in Costa Rica (bare ground, maize monoculture, natural succession, mimicked succession and enriched succession) indicate increases in soil nutrient pools for the various successional treatments relative to the monoculture or the bare ground (Ewel *et al.* 1991). This certainly suggests a positive relation between ecosystem function and biodiversity, although results might have differed if other crop species had been used for the monoculture. Similarly, low number multiple cropping systems tend to produce greater yields than monoculture (Swift & Anderson 1993).

In the more complex reality of most natural ecosystems, the picture is much less obvious. There are, however, some rather simple situations such as microbial communities in Antarctica where species number is positively related to energy flow because of the greater number of chemical sources which can provide energy through microbial oxidation (Woodward 1993). This is analogous to the number of functional groups of microbes and other organisms in much more complex and rich ecosystems.

Clearly some species play more significant roles in ecosystem functioning than others (Vitousek & Hooper

1993). This evolves from the concept of keystone species (Paine 1966). Despite the identification of a number of types of keystone species (Lawton & Brown 1993), the types relate primarily to ecosystem structure and it does not follow that a keystone species is necessarily vital for ecosystem function. In contrast, however, fungal transfer of nutrients by mycorhizas can be significant.

An interesting dimension of the concept of keystone species is provided by the Chesapeake Bay ecosystem (Lovejoy 1993). This ecosystem is of considerable extent, draining significant portions of New York, Pennsylvania, Maryland and Virginia and includes a vast estuary of 103 040 km^2. The American oyster (*Crassostrea virginica*) is today estimated to filter a volume of water equal to the entire bay once a year, but prior to the drastic decline of its population filtered that same volume once a week (Newell 1988). Although oysters never occurred throughout the entire bay, their effect on water clarity and thus the general ecology must have been considerable.

The relatively few experimental manipulations of ecosystems shed a little light on the relationship between biodiversity and ecosystem function. For example, the recovery of ecosystem function by the deforested Hubbard Brook watershed probably related more to biomass than species number (Likens 1985).

The relationship of the stability of an ecosystem to biological diversity is a complicated one (MacArthur 1955; May 1974) but vital to any consideration of sustainable development. An interesting aspect is resistance to invasion by alien species, a serious problem in the United States (U.S. Congress, Office of Technology Assessment 1993) and elsewhere. There does appear to be a greater resistance to invasion by more species rich ecosystems, a concept deriving from pioneering ecologist Charles Elton (1958). Most examples of efforts of alien species relate to the effect on indigenous species; but one relating to ecosystem function involves the invasion of *Myrica faya* in a Hawaii lava field ecosystem. This led to a tenfold change in nitrogen fixation. The recent work of Tilman & Downing (1994) show prairie plots with greater plant diversity are more resistant to severe drought than plots with lower plant diversity.

The relationship of biodiversity and ecosystem function raises the little-explored topic of the extent to which there is redundancy (Walker 1992; Lawton & Brown 1993) of species' function in ecosystems. Undoubtedly, there are species which perform rather similar roles (Hutchinson 1961) although with further knowledge they may be distinguishable (Steinberg & Geller 1993). Redundancy can, in any case, be useful in living systems.

Such analysis can be taken a step further to inquire whether rare species play important roles in ecosystems and their function. In highly diverse tropical ecosystems such as those of tropical forests or coral reefs, there is such a quantity of rare species that taken collectively they do play an important role in ecosystem function. In addition, a rare species may be rare because it is both large and at the top of the foodchain where at least from the perspective of ecosystem structure it may in fact be playing a significant role.

Perhaps more important is that the present role of a rare species may provide little hint of its role or usefulness at other times when environmental conditions vary (Main 1982; Lovejoy 1988). Gap species in a tropical forest are an example, as are the many species which require fire to enhance germination. Ehrlich (1993) points out that it would be difficult to divine the importance of *Cactoblastis cactorum* with respect to the Australia *Opuntia* story from its rather rare and infrequent occurrence in those ecosystems today. A particularly interesting example is a yeast with the ability to reduce mercury (Brunner & Bott 1974). Normally rare in aquatic communities, it becomes abundant during episodes of mercury contamination (natural or anthropogenic), cleans mercury out of the ecosystem and perforce becomes rare once again.

The actual quantification of biodiversity at the level of the ecosystem has already proven to be of considerable pragmatic value. Working on freshwater systems, Patrick and others have developed a considerable body of work relating biodiversity to ecosystem stress (Patrick 1949, 1953, 1961, 1968; Patrick *et al.* 1968, 1969). Essentially the numbers and kinds of species as well as the distribution of abundance between species provide an immensely practical measure of the extent to which the ecology of a river or other freshwater body has departed from normal. This property of quantified biodiversity is essentially the integral of the indicator property of individual species as enhanced or modified by ecosystem structure and internal interactions of those systems. Karr (1991) has used this approach to develop an Index of Biotic Integrity (IBI).

This principle is transferrable, at least in part to terrestrial ecosystems. An experimental grass plot subject to application of nitrogen fertilizer at Rothamsted showed reduction in species number and decreasing equitability of abundance among species over decades. The reverse was true of an abandoned agricultural field in Illinois over a 40 year period (May 1978). The biodiversity of terrestrial ecosystems may in some instances reflect the extent of an ability to resist stress. A set of experiments involving nutrient enrichment of old fields in New York resulted in the more diverse plant community being less sensitive to the treatment. Interestingly, this did not occur at the next trophic level (McNaughton 1993).

This relationship between biodiversity and ecosystem stress suggests that a measure of biodiversity such as that developed by Patrick for freshwater ecosystems could be very useful in the rapidly emerging field of ecosystem management. Simple measures such as alpha (Fisher *et al.* 1943) should be explored. This should not be to the exclusion of particular indicator species or taxa which can be of extreme utility in particular ecosystems and situations. In Australia, for example, ant diversity has proven to be of great value for monitoring ecosystem recovery (Majer 1983). The utility of these kinds of approaches to monitoring the state of ecosystems will depend in turn on the progress made in describing, studying and quantifying life on Earth.

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