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Review article.
The Use of Lichens for Environmental Impact Assessment

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Abstract

The value of lichens for both past and present environmental interpretation and for modelling future changes is demonstrated by reference to detailed and widescale biodiversity and biogeographical investigations. The reliability of lichens as biomonitors, particularly in respect of air pollution, is explored. The importance of baseline data and the value of adopting rigorous protocols for data retrieval are stressed. This is exemplified by personal experience in monitoring radionuclides in Poland before and after the Chernobyl disaster: the genera *Umbilicaria* and *Lasallia* proved ideal for this work, the signatures (ratios) of the different radionuclides taken up by the thalli providing consistent values and reliable baseline data. The role of lichens in environmental impact assessment (EIA) of both quantitative and qualitative changes in air pollution burdens and of a wide range of natural and man-made perturbations, even at a global level, is demonstrated. Lichens, due to their sensitivity, can be used as an early warning system for other biota that, without remedial action, may subsequently suffer stress or indeed extinction through environmental mismanagement. Information gained from our knowledge of how lichens respond to long-term perturbations and short-term upheavals in nature can be applied to the interpretation and monitoring of environmental changes and disasters brought about by a wide range of human activities.

Keywords: Lichens, environmental impact assessment, biomonitors, Chernobyl, radionuclides, air pollution, global warming

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1. Background

The credibility of environmental impact assessment (EIA) is based on experience, the expertise involved predicting environmental consequences on the basis of realistic data reliably accumulated from relevant fieldwork. Such data are derived from pre-impact environmental monitoring of the site under investigation or from pre- and post-impact monitoring of comparable sites elsewhere. One important aspect of this is biological monitoring which is increasingly in demand for the assessment of environmental quality and of risk to human health and safety. It is essential that environmental monitoring is credibly based on standardized procedures and on substantial scientific evidence which should include background measurements to establish baseline data.

Environmental impact assessments for the prediction of environmental consequences resulting from human impacts are based on formal procedures. Assessments which can fulfil these are complex, demanding the services of many scientific specialists, including the lichenologist, as well as economists, sociologists, policy and decision makers, and representatives of interested or affected groups. An environmental impact can only be predicted on the basis of scientific investigations, especially those concerned with a single environmental parameter or variable; the secondary, synergistic consequences, especially those relating to particular local conditions, are less easily predictable. Furthermore, although the nature and extent of a problem can be predicted, its quantification often requires a more sophisticated (and expensive) input to the EIA in terms of modelling, experimentation and expertise. Although such data may not be necessary for many EIAs, attempts to quantify impacts are important even if uncertainties arise through probabilities or margins of error (Seaward, 1999).

2. Biomonitoring

Credible environmental impact assessment is usually based on past experience, much of it derived from environmental monitoring. The use of living organisms, particularly lichens, as indicators of environmental stability is widely recognized. Lichens play varying roles in ecosystems, making specific demands on the physical and other biological components of their environment and responding critically to changes in them. Techniques developed by ecologists are therefore employed on a large scale for 'low technology' environmental appraisals and impact studies where comparable on-site instrumentation would be expensive to install and maintain. However, such investigations may require sophisticated analytical equipment for bioassay back-up and will almost certainly require a detailed understanding of lichen taxonomy to support environmental monitoring and impact assessments. Sadly, expertise in the latter is seriously lacking in many countries due to its omission from college and university curricula.

Of the many published papers dealing with the effects of pollution on lichens, a very large proportion are concerned with field surveys which demonstrate the correlation of the distribution of one or more species with particular pollution burdens (Richardson, 1992; Seaward, 1993). In all probability, the synergistic effects of the sum total of factors involved will never be fully appreciated by means of multivariate analyses, but recent advances in analytical techniques have revealed the very wide range of elements, compounds and radionuclides accumulated by lichens (Markert, 1993), some of which certainly have deleterious effects, even at moderately enhanced levels.

An obvious advantage of using bioindicators such as lichens is that these show the results of a very wide range of human impacts, especially pollutants, on the environment, more particularly on living material – a relevant, if at times rather emotive, approach to determining human impact on the biosphere. It will never be possible to entirely replace direct physical and chemical measurements of environmental factors such as pollutant concentrations with biomonitoring; nevertheless, both approaches are necessary for making a detailed or large-scale survey of environmental disturbances, where the extensive use of technical equipment on-site is costly or impractical.

All too often, monitoring studies based on cartographical interpretations of pollutant accumulation by an organism are deficient due to limitations in field sampling. Isopleths (contours) of pollution loads are frequently delimited on a basis of too few sampling points, very often dictated by the lack of available sampling material or suitable habitat, even landmass, to support credible interpretation. The latter situation is exemplified by monitoring studies undertaken in and around urban and industrial complexes sited alongside major rivers, estuaries and coasts, often favoured locations for such developments. It is all too obvious that not only are biomonitors here restricted by topography, but also the siting of pollution gauges so as to counteract such deficiencies is not feasible (Seaward, 1994). Similar spatial problems also arise from transect studies moving along routes of convenience to the researcher, such as roadway systems, or along ecoclines of study areas adjacent to uplands or shorelines where the performance of monitoring organisms may be dictated more by the factors of the natural ecocline than by the pollutants and the lack of any data from sites where, for example, prevailing winds are influential, and can therefore result in unavoidably biased interpretation.

3. Standardization and Protocols

The Chernobyl disaster typifies the many problems facing the researcher wishing to make temporal and spatial comparisons. Such information on radionuclide levels as is available is fragmentary, measurements prior to the disaster being almost non-existent for most regions, particularly in Central and Eastern Europe.

The problem is further exacerbated by the wide variation in analytical methods and techniques employed, the particular radionuclides selected for investigation, and the expression and interpretation of the data (Seaward, 1994). Standardization is also necessary in terms of the choice of experimental material to be analysed and the sites from which it is collected; these should as closely as possible exhibit uniform physical, chemical and biological properties, and each habitat should be subject to the narrowest possible amplitude of environmental factors (Seaward, 1994; Bargagli and Nimis, 2002). The potential for inconsistency through the use of a number of different species, each differing in its inherent capacity to accumulate the various radionuclides, and collected from a wide range of substrata and habitats experiencing various environmental conditions is all too obvious from the literature.

In view of the Chernobyl disaster on 26 April 1986, it was fortunate that the lichen monitoring programme initiated in 1978 throughout south-west Poland (Seaward et al., 1981) had established baseline radioactivity data (Kwapulinski et al., 1985a,b). These revealed that elevated background levels of radionuclides already existed at numerous sites due to inherent geological features, nuclear weapon testing prior to the mid-1960s, and, most importantly, recent emissions of radioelements from the stacks of power stations burning brown coal (lignite).

Naturally, the Chernobyl disaster exacerbated the problem, as testified by the measurements made of similar lichen material collected from the same sampling sites in 1986, 1988 and 1990. ^{137}Caesium measurements, for example, showed startling increases, up to 165-fold, on those monitored prior to the disaster; such multiplications of levels must, however, take into account the fact that enhanced levels already existed at many sites.

Valid interpretation of radionuclide levels in Polish lichens has only been feasible through a detailed knowledge of existing levels of accumulation in particular species, in this case species of *Umbilicaria* and *Lasallia*, at the same sites over a period of time (Seaward, 1992a). It is strongly recommended that similar on-going biomonitoring programmes adopt standardized techniques and rigorous methodology in order to credibly establish comparative temporal and spatial analyses.

The proper use of living organisms as indicators and samplers of ambient conditions is a valuable resource for the environmental impact assessor. Provided there is sufficient resource material, and that rigorous protocols for collection are adopted, periodic sampling of them for pollutant levels has proved valuable in documenting environmental change. It should be emphasised that lichens are very slow-growing and that any sampling should be kept to a minimum not only in terms of the availability of a future source for analysis but also for their conservation.

4. Reliability and Consistency

How reliable are lichens as monitors of the environment? As mentioned above in terms of the Chernobyl work, each species has the capacity to accumulate its own level of particular pollutants, so the determination of absolute values has little meaning. However, provided a rigorous protocol is adopted with the same species analysed at each site, credible comparative information for wide-scale environmental impact interpretation can be established. In the light of this it was reassuring to note the consistency of the relative amounts of the various radionuclides accumulated (signature) intra- and inter-specifically by lichens consequent upon the Chernobyl disaster, the $^{134}Cs : ^{137}Cs$ ratio, for example, being 0.54 ± 0.04 ($n = 32$) for all sites studied (Seaward et al., 1988). Similarly, it was interesting to note the consistency in the relative levels of uptake in relation to altitude (Fig. 1), the values for lower v. higher altitudes displaying the same characteristics for pre- and post-Chernobyl data (Seaward, 1992a).

Such consistency adds credibility to the establishment of base-line monitoring data to be used in future environmental surveillance and impact assessment. Furthermore, lichens can be used for retrospective field sampling of such pollutants as heavy metals through the careful use of well-localized and dated herbarium and databank material (MARC 1985). Comparisons of certain element concentrations for suitably documented environmental material collected over the past 200 years will, however, prove valuable in measuring changes in the quality of our environment and provide background measurements in the event of major environmental impacts and disasters (Seaward, 1994). The provision of banks of lichen material and their substrata, assembled by periodic sampling from clearly-defined sites, may be considered in this context (e.g. Lawrey and Hale, 1981); such material may well be more profitably interpreted when even more sophisticated equipment has been developed and/or other chemicals, hitherto not monitored, are of cause for concern.

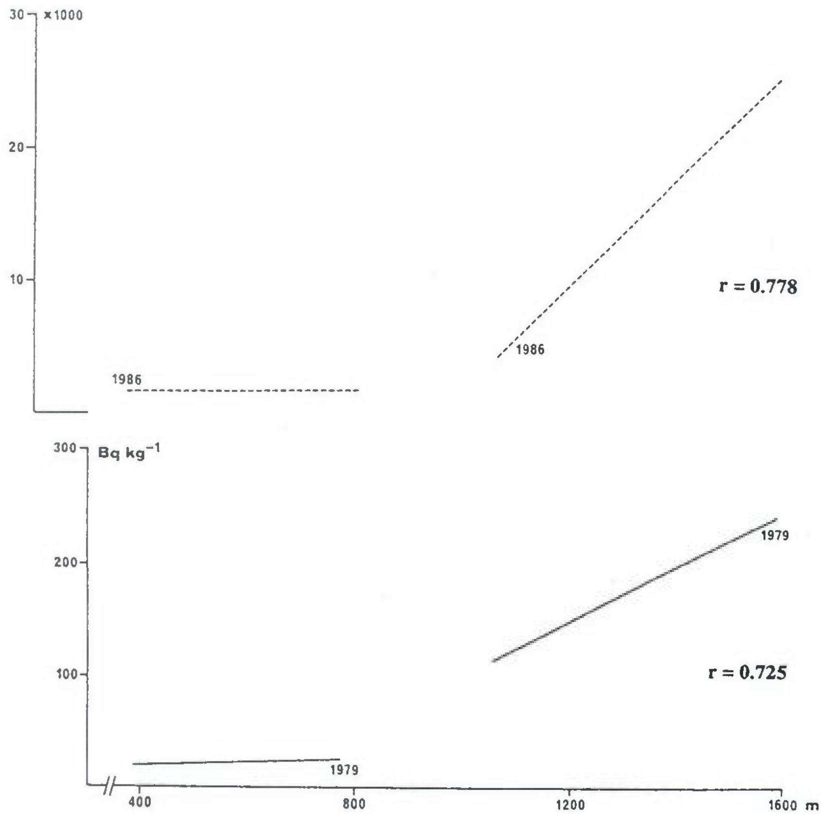

Figure 1. Relationship between altitude (m) and ^{137}Cs content (Bq kg^{-1}) of *Umbilicaria* and *Lasallia* spp. collected from S.W. Poland in 1979 and 1986 (after Seaward, 1992a).

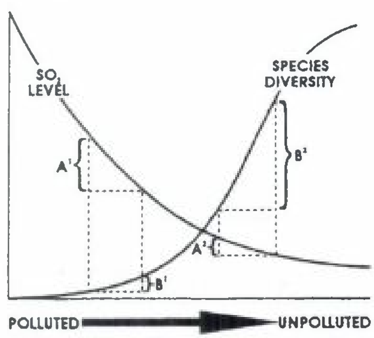

Figure 2. Model showing the relationship between species diversity and SO_2 level (Seaward, 1993). Note that major reductions in SO_2 (A^1) at the more polluted end of the scale will have little effect on biodiversity (B^1), whereas as the other end of the scale a minor increase in SO_2 (A^2) would dramatically reduce biodiversity (B^2).

5. Modelling Pollution Burdens

There is a negative relationship between species diversity and pollution burden, and from zonal studies of lichens in polluted areas it has been shown that the inner distributional limit of particular species can be clearly defined. Lichens, through their highly specific demands on environmental resources, can be usefully employed in pollution surveys since species are hierarchical in their susceptibility to a particular pollution burden and a detailed knowledge of extinction points can be used to construct critical bioindication scales for use in environmental impact assessment. However, such scales tend to be logarithmic in nature (Fig. 2): extensive work on lichens has shown that major reductions in the level of a pollutant at the more polluted end of the scale may have little, or indeed no, effect on species diversity, but in a less polluted situation, the effect is exponential with only a minor increase in the pollutant dramatically reducing biodiversity (Seaward, 1993, 1997a).

Long-term mapping programmes at a local, regional and national scale can now be considered for international surveillance, or indeed for monitoring global impacts. Local to national studies have provided suitable data to model rising and falling air pollution levels, particularly sulphur dioxide, by biodiversity counts, interpretation of assemblages or indeed the performance of a particular species, such as *Lecanora muralis* (Henderson-Sellers and Seaward, 1979), or genus, such as *Usnea* (Seaward, 1992b, 1998). This type of investigation has also demonstrated that there is a time-lag between the time particular lichens re-establish themselves and the time when the pollution had actually been reduced to a level to allow this to happen according to biomonitoring scales; in the case of *Lecanora muralis* this time lag was found to be approximately five years (Henderson-Sellers and Seaward, 1979). Hence, in ameliorating environments lichens reflect pollution levels of times past rather than current burdens.

Such studies have also demonstrated in recent decades the qualitative as well as quantitative shifts in the pollution burden, the delivery of sulphur dioxide as gaseous dry deposition succeeded by wet deposition (acid rain) being mirrored by the behaviour of different lichens in terms of their ecology and geography (Seaward, 1987, 1992b). Irrespective of the mode of delivery, overall sulphur dioxide levels have fallen dramatically in Britain and elsewhere and multivariate analyses of factors obtaining in urban areas have less convincingly demonstrated a relationship between lichen diversity and this pollutant (Seaward, 1993). In such circumstances, lichens are incapable of monitoring SO_2 which has been reduced to below the detection limit by those species inhabiting urban and industrial environments. Although the renaissance of urban lichen floras is mainly due to this, eutrophication, and indeed hypertrophication (excessive nutrient enrichment derived from agricultural, industrial and vehicular sources), have also been responsible for the establishment of nitrophilous assemblages, thereby increasing biodiversity (Seaward, 1997a). The phenomenon of hypertrophication is not restricted to urban areas and wide-scale changes to rural lichen floras are consequent upon agricultural practices, some of which have been masked in the past by the sulphur dioxide burden (Seaward and Coppins, 2004).

6. Other Perturbations

As well as monitoring pollution, it is also possible to analyse shifts in distributional limits of selected lichens as a consequence of a wide range of perturbations, both natural and man-made, even at a global level. Since lichens form an important component of the complex web of life, their disappearance affects the balance of nature to a surprising degree. This is particularly the case in boreal and tundra zones, high altitudes, cold deserts, dune systems, semi-arid lands and deserts, and even urban areas, where they provide vital links in food chains and are important in community development and succession on rocks and soils.

Natural phenomena, such as retreating glaciers, and disasters, such as avalanches, volcanic eruptions, earthquakes, seismic landslides and unstable debris-flow, all impact on the lichen flora, the disappearance of which from particular substrata can be critical (see below). Rock and soil destabilization through human impacts will have similar repercussions on the lichen flora. From detailed field studies and remote sensing (cf. Nordberg and Allard, 2002), it should be possible to monitor changes in the lichen flora of terrestrial environments resulting from flooding (Gob et al., 2003), displaced snow-lines (cf. Sonesson et al., 1994), episodic snow-kill (Benedict, 1991), avalanches (McCarroll, 1993), seismic landslides (Bull et al., 1994) and other unstable debris flows (e.g. Innis, 1983), and retreating glaciers as a result of climatic shifts. Such time-space investigations can exploit fully lichenometrical techniques widely developed over the past few decades (Innes, 1985).

Of particular interest, and indeed concern, are the sensitive lichen-dominated ecosystems which probably cover 8% of the world's terrestrial surface, mainly in hot and cold deserts, alpine zones and coastal areas. Such remote areas are no longer free from human impacts which range from shifts in land-use to widespread dispersal of pollutants, some affecting global warming; the depletion of the stratospheric ozone layer, resulting in an increase in ultraviolet radiation, will also impact on polar lichen floras, the full implications of which have yet to be investigated (cf. Quilhot et al., 1996).

Although information on more widespread effects of global warming on lichens is still limited (e.g. Cornelissen et al., 2001; Insarov and Insarova, 2002;

Insarov and Schroeter, 2002; Tømmervik et al., 2003), some preliminary evidence to support this phenomenon has been provided by researchers in The Netherlands (Van Herk et al., 2002) where there has been a demonstrable increase in the proportion of widespread tropical species and a decline in arctic-alpine and boreal species. There is less convincing evidence for this in the British Isles, but several species, such as *Xanthoparmelia soredians* (Seaward and Coppins, 2004), have been targeted for special attention as potential monitors of this effect.

Elsewhere global warming will lead to retreating snow-lines, to lowered lake shore and river bank lines and to a rise in sea-level, all areas which currently support distinctive zonations of lichens, particularly on rocks, that can be easily monitored. Land mismanagement, as impacted on the lichen floras, has been demonstrated in the case of tundra ecosystems, arid soil crusts (Belnap et al., 2001; Evans et al., 2001), replacement of natural substrata (ranging from urban landscapes to ski-slopes) and indirect hydrological effects due to lowered water-tables or impounded water.

Field studies have established the importance of lichens in contributing to environmental modification. Changes in reflectance and in ecophysiological responses, such as photosynthetic activity, chlorophyll levels, gaseous exchange and water absorbance, brought about by anthropogenic disturbances to lichen-dominated communities can be detected by remotely sensed images (cf. Eldridge and Green, 1994; O'Neill, 1994). As a consequence, the environmental significance of variations in these activities is increasingly being recognized. In arctic and alpine areas, lichens possess specialised physiological mechanisms enabling them to photosynthesise and take up water at low temperatures (e.g. Kappen, 1989). Lichens may also be effective as ice-nucleating agents (Kieft, 1988) and therefore can initiate freezing of supercooled water at relatively warm temperatures. Temperature differences in remote areas, such as polar regions, influenced by the presence or absence of lichen cover, could no doubt be detected by remote sensing techniques.

Furthermore, lichen denudation, if not ameliorated, could have climatic repercussions and exert a measurable influence on global warming (cf. Schwartzman and Volk, 1989). The potential for global warming due to the disappearance of epilithic lichens over a very large area of the Canadian Shield as a direct consequence of atmospheric pollution emanating from the nickel smelting operations at Sudbury (Seaward, 1996) has fortunately subsided due to pollution abatement measures, the barren rock surfaces now being recolonised by lichens, thereby restoring their light-absorbing ability (cf. Petzold and Goward, 1988; Rollin et al., 1994; Bechtel et al., 2002).

Lichens, due to their sensitivity, can be used as an early warning system for other biota that, without remedial action, may subsequently suffer stress or indeed extinction through environmental mismanagement (Seaward 1997b).

Information gained from our knowledge of how lichens respond to long-term perturbations and short-term upheavals in nature can be applied to the interpretation and monitoring of environmental changes and disasters brought about by a wide range of human activities.

7. Concluding Remarks

Monitoring air, water and soil contamination by biotic and abiotic materials will be increasingly important for assessing environmental quality. Therefore, it is essential that environmental monitoring and environmental impact assessments are credibly based on standardized procedures and substantial scientific evidence. It is all too evident that many EIAs have been poorly serviced in terms of environmental monitoring based on scientific rigour. EIAs have become diluted through the misapplication of the word 'environmental': its use to qualify policy, reporting, performance and management is frequently approached from a purely business standpoint. Whilst accepting that environmental sense often makes economic sense, EIAs have provided companies and authorities with economically-biased procedures to monitor their business performance rather than their environmental performance. There is a greater need for EIAs to return to basics, where predictions on the fate of both the natural and the man-made environments are based on realistic and relevant data derived from scientific studies which can be integrated with the economic, sociological and anthropological aspects of the assessment. Lichenologists clearly have an important role to play in this respect by providing credible environmental monitoring based on rigorous protocols and by predicting the outcome of proposed environmental perturbations from exhaustive field studies.

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