Ecology and Management of Biological Soil Crusts: Recent Developments and Future Challenges

David Eldridge

The Bryologist, Vol. 103, No. 4. (Winter, 2000), pp. 742-747.

The Bryologist 103(4), pp. 742–747

INVITED ESSAY

New Frontiers in Bryology and Lichenology

Ecology and Management of Biological Soil Crusts: Recent Developments and Future Challenges

DAVID ELDRIDGE
Centre for Natural Resources, Department of Land and Water Conservation, c/o School of Geography,
University of New South Wales, Sydney, NSW, 2052, Australia

Biological soil crusts, often referred to in the North American literature as microbiotic, cryptogamic, cryptobiotic, or microphytic crusts, are the dominant biological soil surface feature in arid and semi-arid landscapes. Crusts comprise a complex assemblage of organisms such as mosses, liverworts, cyanobacteria, algae, lichens, fungi, and bacteria growing on and within the uppermost layers of the soil. Their close association with the soil means that they are subject to processes operating at the interface between the biosphere and the atmosphere. This makes them useful indicators, or surrogates, of activities that impact upon the soil or the atmosphere.

The close association with the soil surface means that biological crusts and their component organisms play vital roles in ecosystem processes. They stabilize the soil against water and wind erosion, regulate the flow of water into soils, provide a sink for soil carbon, and organisms in the crust produce nitrogen that is often used by vascular plants. Biological soil crust organisms also provide favorable sites for the establishment and survival of vascular plant seedlings, and provide niches for soil invertebrates that are important for decomposition and mineralization processes.

During the past decade there has been increased interest in the roles of biological crusts in soil and ecological processes. Recent reviews (e.g., Eldridge & Greene 1994; Evans & Johansen 1999; West 1990) have reinforced the notion that crusts are essential components of healthy, functional ecosystems. Soil crust are now being included in routine assessments of rangelands (Green et al. 1994), and their roles in carbon and nitrogen production and water movement in desert areas are receiving renewed attention (Eldridge et al. 2000). Moreover, the scientific community is embracing the concepts of ecologically sustainable development as it applies to grazing systems, and crust organisms are seen as essential components of both local and regional biodiversity.

Soil crust ecology has now moved from a phase of discovery to one of consolidation. In the early 1970's, Roderick Rogers pioneered the early work on soil crust lichens in Australia at a time when lichen taxonomy was in its infancy. The 1980s and 1990s were followed by more work on the ecology and distribution of crusts mainly in North America and Australia (West 1990). However, despite the large amount of work on crust organisms worldwide, there is still little known about their distribution at a local level and how they are affected by land management. The challenge over the next decade is to determine the links between crust organisms and landscape health, and to educate the general community and land management agencies about their importance as indicators of healthy, productive ecosystems (Scott et al. 1997).

A comprehensive review of the roles of biological soil crusts in ecological processes is beyond the scope of this article, and excellent reviews are already available in the literature. In this review, I focus on recent developments in the ecology and management of soil crust organisms. Firstly I discuss how land managers in northern Israel are using biological soil crusts to maximize the harvesting of water for agriculture, and research on soil crust organisms as sinks for atmospheric compounds. Secondly, I discuss the challenges faced by soil crust ecologists in educating governments, land managers, and the scientific and general community.

RECENT DEVELOPMENTS IN SOIL CRUST ECOLOGY AND MANAGEMENT

Soil crusts for harvesting essential resources.— Biological soil crusts are increasingly being recognized as keystone elements of desert ecosystems.

Publication No. CNR00.063 of the Centre for Natural Resources.

0007-2745/00/742–747$0.00/0

Despite their putative role in water movement in desert soils, there is a wide disparity of views regarding their beneficial or otherwise role in infiltration. Research from eastern Australia suggests that crusts enhance infiltration in degraded soils, but have minimal influence in soils in good condition (Eldridge & Greene 1994). Conceptual models have been developed that link the effect of crusts on water flow to soil condition and management. Within this framework, land managers can maximize infiltration of water in degraded landscapes by promoting cover of biological soil crusts.

In the Middle East, however, crusts are being managed to minimize infiltration and therefore maximize the flow of water from rangelands to enhance tree growth for either agriforestry or recreation. The *shikim* system of Israel's northern Negev is a landscape structure composed of soil hummocks supporting perennial shrubs surrounded by areas of biological soil crust, with human-made pits constructed on the uphill side of long, low contour banks constructed at varying intervals down the slope (Shachak et al. 1998). The cyanobacterial and lichen-covered soils in the northern Negev repel water, restricting infiltration, and therefore promoting runoff (Eldridge et al. 2000). The crust component sheds water, nutrients, and soil onto the shrub hummocks that receive more water than they normally would from rainfall alone. This makes the shrub patches the most productive components of the landscape. The crust, however, often produces more runoff than can be used by the shrub hummocks, and this run off accumulates in the human-made pits. In the *shikim* system, therefore, the extent and the spatial distribution of the soil crust is a major factor in controlling the distribution of primary production between the vegetated and human-made part of the landscape. By maintaining and utilizing these areas of crust, and varying the distances between the contour banks, land managers in the northern Negev are able to support a range of fruit and forestry trees in areas that would normally have insufficient rainfall to support forestry.

Soil crusts, atmospheric health, radionuclides, and mineral exploration.—It is widely known that lichens have the capacity to absorb different atmospheric pollutants making them useful bioindicators of environmental stress. This monitoring takes the form of elemental analysis of lichen tissues, mapping of species distributions, or transplant studies. In general, however, much of this research has been directed at macrolichens, with little emphasis on the more diminutive lichens (or bryophytes) inhabiting soil crusts. Lichens have been used to detect changes in atmospheric conditions in relation to emissions from motor vehicles and industrial plants (e.g., Garty et al. 1996), and this has the potential to be extended to major centers of populations in rangeland areas (e.g., Salt Lake City in the western United States) where photochemical smog and industrial pollution have increased over the past decade. In Kalgoorlie, Western Australia and Newcastle, New South Wales, studies of soil lichens have demonstrated the links, though ill-defined, between soil crust floristics and atmospheric pollution along gradients of atmospheric pollution in the vicinity of smelters.

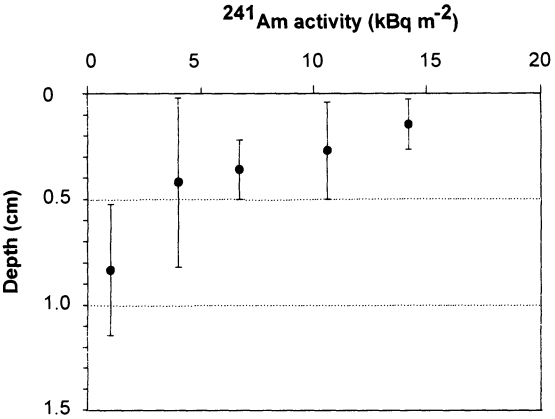

FIGURE 1. Mean (+ standard deviation) of ^{241}Am activity (kBq m^{-2}) on a sand dune at Plume Sample Site No. 5, Maralinga (from Ferris et al. 1998).

Research conducted at the former nuclear test site at Maralinga in northwestern South Australia has shown that microphytic crusts are able to physically retain contaminated radionuclides in surface soils. The surface contamination of plutonium (Pu), as measured by the presence of Americium (^{241}Am) indicates that 85% of measurable ^{241}Am activity is confined to the upper five mm of the soil and 95% within the upper 1.2 cm, both within the biologically active crust zone (Ferris et al. 1998; Fig. 1). This study indicated that the microphytic crust has the ability to physically retain ^{241}Am and therefore Pu in the surface soils. Thus from the viewpoint of entry Pu and ^{241}Am into the biosphere, the crust has maintained these radionuclides in the most biologically active sections of the soil surface where they are potentially available for soil biota that use the crust for habitat or food (Ferris et al. 1998). The health risk from ingestion of these radionuclides is probably minimal provided that activities do not destroy the soil crust. These radionuclides, which have a long half-life are likely to enter the food chain through predation by soil organisms. Little is known, however, about the rates of bio-degradation of these radionuclides by soil biota and further research is warranted.

Recent unpublished research has suggested that mosses and lichens are potentially useful organisms for providing evidence of covert nuclear reprocessing activity (M. Hotchkis, pers. comm.). Iodine^{139} has an extremely long half-life, and by studying the concentrations of isotopes of iodine (I^{139}) in biological material, and comparing them with background levels known from global studies, scientists can determine whether reprocessing has occurred. Research has also indicated that soil crust lichens may have a role to play in mineral exploration (Hill et al. 1999). The distribution of crust organisms is tightly tied to soil pH, with crusts often reaching their greatest development in soils where the pH exceeds nine. Gold appears to be most closely associated with parts of the regolith carbonate profiles where biological processes are most prevalent. These regolith carbonate deposits also support the highest cover and diversity of biological soil crusts, the members of which may accumulate gold and other trace metals (Hill et al. 1999). Thus, biological soil crusts can potentially be used as indicators of trace metal deposits.

Soil crusts and carbon sequestration.—It is now being accepted that biological soil crusts are important global sinks for atmospheric carbon. Biological soil crusts, comprising cyanobacteria, terrestrial algae, lichens, and mosses, contribute organic carbon fixed through photosynthesis, directly to the soil ecosystem (Beymer & Klopatek 1992). Studies from the semi-arid woodlands in western NSW have demonstrated substantially higher levels of organic carbon beneath soil crusts compared with adjacent crust-free soils (Eldridge & Greene 1994). This organic carbon is stored in the top centimetre of the crust where it is relatively stable, provided that disturbance and animal trampling are not excessive. In Australia, a system of carbon credits is now being introduced as a way of trading in carbon. Carbon sinks, such as forestry plantations, grasslands, and conceivably intact areas of soil crust, are being incorporated into an emissions trading system by allocating credits for the amount of carbon sequestered. The owners of these areas where carbon is stored then sell these credits in an emissions trading system. Companies purchase carbon credits in order to offset their carbon dioxide emissions and to meet their responsibilities under the Kyoto Protocol to the United Nations Framework Convention on Climate Change. Large areas of rangelands in North America, North Africa, Asia, and Australia have landscapes where soil crusts are the dominant biological soil feature. Thus there is the potential not only to reduce carbon emissions by maintaining healthy soil crusts, but to place an economic value on soil crusts in terms of their ability to sequester and maintain carbon in the soil.

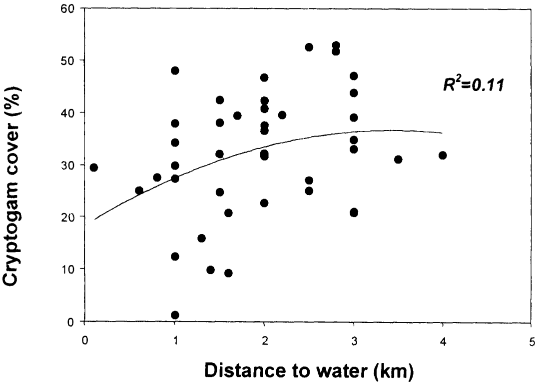

FIGURE 2. Relationship between cryptogam cover and distance to water in a 10 year monitoring study near Cobar, NSW, Australia.

FUTURE CHALLENGES: SOIL CRUSTS, LANDSCAPE HEALTH, AND EDUCATION

The field of soil crust ecology is an exciting one. The science and management of soil crusts integrate a number of broad disciplines from bryology and lichenology to soil science, geomorphology, and terrestrial ecology. Despite the gains over the past two decades, more research and development needs to be undertaken. In my view to make progress we need to improve the way in which we package our information in order to make it more applicable to managers. At the same time there is a need to attract more specialists into the field of cryptogamic botany to undertake basic research that has lagged far behind that carried out in vascular plants. There are three areas where particular attention needs to be focussed; these are 1) linking soil crust conditions with landscape health, 2) promoting soil crust organisms to the wider community, and 3) protecting crust organisms through legislation.

Establishing links between crusts, landscape health and management.—While many soil crust practitioners acknowledge the close links between biological soil crusts and landscape (rangeland) health assessment, there have been few attempts to include soil crusts and their component organisms in routine land assessment. Systems have been developed in Australia to characterize soil health in terms of readily identifiable surface features, including soil crust cover, which are moderately well correlated with indices of stability, nutrition, and infiltrability (Tongway 1995). Long-term monitoring of crust cover is included in routine assessment of condition at more than 350 rangeland sites in western NSW, Australia. This allows useful relationships, such as changes in cover in relation to stocking intensity in vegetation communities, to be

TABLE 1. Description of morphological groups of cyanobacteria, lichens, and bryophytes (from Eldridge & Rosentreter 1999).

Morphological group	Description	Representative genera
Cyanobacteria		
Cyanobacteria	Blue-green, dark red, or blackish single-celled, colonial or thread-like strands in the soil.	*Microcoleus, Nostoc, Oscillatoria, Scytonema*
Lichens		
Gel-like lichens	Lichens with an unlayered thallus becoming jelly-like when wetted. They tend to be blackish in color and turn blue-green when wet. They have an algal partner which is a cyanobacterium which generally allows them to fix atmospheric nitrogen.	*Collema, Leptogium*
Crusty lichens	Lichens forming a crust-like growth that is tightly attached to the substrate.	*Aspicilia, Caloplaca, Diploschistes, Lecidea*
Scaly lichens	Lichens with thalli occurring as discrete scales, warts, or flakes that can be ear-shaped, convex, or concave.	*Acarospora, Buellia, Catapyrenium. Peltula, Psora*
Leafy/Shrubby lichens	Three-dimensional lichens. Leafy (foliose) lichens tend to be flattened, with a definite upper and lower surface. Shrubby (fruticose) lichens tend to be ropy or shrub-like, and are sometimes branched.	*Cladia, Cladina, Heterodea, Parmelia, Physconia,* some *Xanthoparmelia*
Bryophytes		
Mosses	Plants green and erect; leaves (with mid-vein) arranged around the stem.	*Bryum, Crossidium, Didymodon, Pottia*
Liverworts	Prostrate, green, leafy plants without a mid-vein (leafy liverwort), or Y-shaped and prostrate on the soil surface with roughly a triangular cross-section (strap-like liverwort)	*Clevia, Riccia*

determined (Fig. 2). Monitoring soil crust and therefore soil health provides land managers with an extra tool with which to make management decisions based on the health of the ecosystem. Despite some advances however, non-vascular soil organisms have largely been ignored in routine assessment of landscape health.

Detailed assessment of diversity of crust organisms at both regional and local scales is complicated by the difficulties experienced with field identification of bryophytes and lichens. This is exacerbated by the fact that soil crust organisms are generally small, cryptic, and poorly developed due to the hostile environment in which they live. Soil temperatures often in excess of 60°C in summer result in poor specimens, making positive field identification problematic. Over the past decade, renewed interest in diversity of cryptic organisms such as invertebrates has seen the development of rapid biodiversity assessment as a monitoring tool (see Oliver & Beattie 1996). In Australia and the United States, recent research has explored the use of morphological groups rather than the traditional Latin binomial approach as effective surrogates for monitoring biological soil crusts in arid areas (Table 1, Eldridge & Rosentreter 1999). The strong relationships between morphology and function of biological soil crust organisms in relation to disturbance and ecological processes means that they are useful indicators of management. Empirical data for an area of more than 600,000 km^2 of eastern Australia have indicated that the yellow foliose morphological group comprising foliose lichens of the genera *Heterodea*, *Xanthoparmelia*, and *Chondropsis* is associated with well-managed, stable, and productive landscapes, while morphological groups such as black gelatinous (*Collema* spp.) or brown warty (*Endocarpon*, *Catapyrenium*) lichens occurred independently of condition (Eldridge & Koen 1998). The results of this and other work on surrogate species gives land managers the ability to monitor, through minimal training or the use of para-taxonomists, more sites more rapidly, compared with using traditional taxonomic methods. While morphological groups may be too coarse to allow the detection of rare species, they can provide valuable information about temporal and spatial changes in soil crust communities at a much greater number of sites. Future challenges therefore will be to train field operators to be able to identify morphological groups, while at the same time examining the relationships between ecosystem health and function at a greater number of landscapes.

Enhancing the image of soil crust organisms.—There is a need to continually adopt novel ways of packaging science to the broader community, whether they are politicians, pastoralists (ranchers), or the general community. Recently, I was invited to give a presentation at the 3rd Annual Mildura Arts Festival. The theme of the festival was 'Where Art meets Science', and various presenters demonstrated ways in which art can not only empower scientists but can be a effective medium for educating the broader community. Soil crust organisms were presented not as arcane objects, but as colorful, artistic, living organisms of varying textures and colors which play an important role in the ecology of dryland ecosystems. Participants were given the opportunity to handle specimens, and to observe how their color and consistency changed when wetted. This inevitably lead to a series of questions relating the importance of crusts, how they should be protected, and how artists can participate in public education programs to protect these and other cryptic organisms.

In my opinion, one of the greatest challenges for those working with biological soil crusts is to raise their status in the general community. This can be done through education programs at schools, forays, talks to naturalist and community groups (e.g., Rotary), field guides, and general publicity material including a greater use of the Internet.

Conservation of non-vascular plants.—In Australia, conservation of biodiversity is enshrined in a number of international treaties and obligations, requiring governments to conserve biodiversity. At the state and federal levels, the Threatened Species Conservation Act (1995) and the Environmental Protection and Biodiversity Conservation Act (2000), respectively call for nominations of threatened plants and animals and threatened communities to be submitted to a threatened species register. In New South Wales, a threatened *Pseudocephallozia* and a community of fungi are listed on the Threatened Species Schedule but as yet no soil lichens or bryophytes are listed. A recent publication on the conservation status of non-vascular plants-marine cryptogams (Scott et al. 1997) identified about 340 cryptogamic species (lichens and bryophytes only) as being either endangered (102), threatened (144), or vulnerable (92) based on expert knowledge at the time and limited herbarium records; however, this number is likely to be much greater. Most of these species are known from only one record, and consequently little is known about their ecology or the likely impacts of development upon their populations. Listing of individual species or communities, at either a state or federal level, provides some protection for the species against inappropriate land management, but its greater benefit is that it compels governments, through legislation to consider the likely impacts of proposed developments on populations and communities of cryptogams. It also paves the way for greater employment opportunities for those with experience in cryptogamic botany.

In Australia, there is renewed interest in non-vascular organisms in general, and soil crust species in particular, and nominations of species or communities on threatened species schedules is seen as one way of raising the profile for these organisms and securing funding for the employment of professional bryologists, lichenologists, and mycologists. Over the past 10 yr there has been a steady decline in the number of full-time personnel working on the study of non-vascular organisms in Australian institutions. Few people are being attracted to taxonomic institutions and there does not appear to be a willingness by governments to commit resources to research and development within the non-vascular field. The listing in the legislation of some threatened or endangered 'flagship' cryptogams, which by necessity need to be large and easily identifiable, as occurs in some European countries, appears to be one way of addressing the dearth of skilled cryptogamic specialists, while at the same time providing protection for threatened cryptogams and their communities.

LITERATURE CITED

BEYMER, R. J. & J. M. KLOPATEK. 1993. Potential contribution of carbon by microphytic crusts in pinyon-juniper woodlands. Arid Soil Research and Rehabilitation 5: 187–198.

ELDRIDGE, D. J. 1998. Trampling of microphytic crusts on calcareous soils and its impact on erosion under rain-impacted flow. Catena 33: 221–239.

——— & R. S. B. GREENE. 1994. Microbiotic soil crusts: a review of their roles in soil and ecological processes in the rangelands of Australia. Australian Journal of Soil Research 32: 389–415.

——— & R. R. ROSENTRETER. 1999. Morphological groups: a framework for monitoring microphytic crusts in arid landscapes. Journal of Arid Environments 41: 11–25.

———, E. ZAADY & M. SHACHAK. 2000. Infiltration through three contrasting biological soil crusts in patterned landscapes in the Negev, Israel. Catena 40: 23–36.

EVANS, R. D. & J. R. JOHANSEN. 1999. Microbiotic crusts and ecosystem processes. Critical Reviews in Plant Sciences 18: 183–225.

FERRIS, J. M., R. A. HOFFMANN, R. A. JEFFREE & J. R. HARRIES. 1998. Plutonium contamination and the microphytic crust at Maralinga. A Report to the Department of Primary Industries and Energy, Australian Nuclear Science and Technology Organisation, Lucas Heights.

GARTY, J., M. KAUPPI & A. KAUPPI. 1996. Accumulation of airborne elements from vehicles in transplanted lichens in urban sites. Journal of Environmental Quality 25: 265–272.

GREEN, D., D. HART & J. PRIOR. 1994. Rangeland Study Site Manual Part 1. Site selection and field measurement procedures. Soil Conservation Service.

HILL, S. M., K. G. MCQUEEN & K. A. FOSTER. 1999. Regolith carbonate accumulations in western and central western NSW: characteristics and potential as an exploration sampling medium, pp. 191–208. *In* Regolith '98: New Approaches to an Old Continent, Cooperative Research Centre for Landscape Evolution and Mineral Exploration.

OLIVER, I. & A. J. BEATTIE. 1996. Designing a cost-effective invertebrate survey: a test of methods for rapid assessment of biodiversity. Ecological Applications 6: 594–607.

SCOTT, G. A. M., T. J. ENTWISLE, T. W. MAY & N. G. STEVENS. 1997. A Conservation Overview of Australian Non-Marine Lichens, Bryophytes, Algae and Fungi. Environment Australia, Canberra.

SHACHAK, M., M. SACHS & M. ITSHAK. 1998. Ecosystem management of desertified shrublands in Israel. Ecosystems (in press).

TONGWAY, D. J. 1995. Monitoring soil productive potential. Environmental Monitoring and Assessment 37: 303–318.

WEST, N. E. 1990. Structure and function of microphytic soil crusts in wildland ecosystems of arid and semiarid regions. Advances in Ecological Research 20: 179–223.