10 Environmental Significance of Lichens and Biodeterioration

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Abstract

This chapter underlines the environmental values of lichens, an important part of biodiversity on Earth, and at the same time addresses the subject of biodeterioration in detail. Diversity and sociology of lichens, ecological factors effective on growth and distribution of the lichens, bioindicative and biomonitoring roles of lichens in the air pollution and also roles of lichens in ecological events such as erosion prevention, succession and soil formation in nature were mentioned under the brief headings. Information was given on the occurrence of biological deterioration "biodeterioration", both physical and chemical properties and functions of the event and the organisms causing the biodeterioration. Biological deterioration occurring in the presence of living organisms such as lichens, fungi and mosses known as eroding stone surfaces, while qualifying as damaging in the case of historical monuments and works of art, also represents a fundamental process of the biosphere. The literature on biodeterioration of stone monuments and artiefacts, especially by lichen species and other organisms, and also the protective methods in this area have been reviewed. This compilation is intended to provide information on the importance of lichens for the environment as much as it is for biodeterioration and is thought to be a guide for the establishment of management and conservation strategies today.

Keywords

Biodeterioration · Biodeteriogen · Lichen diversity · Monument · Stonework · Biological weathering

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V. Shukla, N. Kumar (eds.), *Environmental Concerns and Sustainable Development*,
https://doi.org/10.1007/978-981-13-6358-0_10

10.1 Introduction

Lichens are an important part of biodiversity with more than 20,000 species, especially in clean air habitats, spreading from poles to deserts in different ecosystems. Some of them are in the rock slits or tree bark in the countryside, like a hidden, indeterminate crust, and some of them are obviously leafy, shrubby and threadlike and have a wide variety of colours and appearances. The lichens that distribute on most of the Earth's ecosystems live on specific environs the so-called substrate which can be natural environments such as rock, stone, soil and tree or sometimes man-made environments such as tile, wall, concrete and marble. For the last 30 years, almost all discussions on nature conservation have been about biological diversity and ways to protect it. The lichens are not excluded from these studies, and many current works highlight the importance of preserving lichens and habitats, since the natural roles of these organisms are of great importance in the shaping of the physical and biological environment of our planet.

Lichens are among the cryptogams such as algae, bryophytes and liverworts which are called hidden plants because of their small sizes in the realm of life, and they are included in the terrestrial fungi that reproduce via spores. Slowly growing lichens are very sensitive to air pollutants, although they are very durable and long-lasting in extreme conditions. Certain lichen species are indicative of the level of air pollution. Since air pollution affects lichens, their primary consumers and therefore their hunters are also negatively impacted. Thence much more extensive research on the effects of environmental pollutants is needed.

One of the characteristics of algae, mosses, fungi and lichens that can survive by adhering to man-made stone substrates is that they cause these stone surfaces to deteriorate in time. "Biodeterioration" (biological weathering) of stone monuments is one of the main interests of researchers working on the conservation of cultural heritage. The most particular biological agents of deterioration on stone surfaces in nature and also on stone monuments and works of art are lichens, mosses, algae, fungi, bacteria and other microorganisms. Some plants and animals may also participate. The term "biodeterioration" is defined as damage to materials that is caused by living organisms, meaning to the breakdown of materials by microbial action as a result of physical and/or chemical processes. Lichens and mosses capturing organic residues such as dust coming with the wind, plant fibres, seeds, dead insects and animal residues on rock contribute to the formation of soil. Changing of carbon dioxide (released from respiration of the organisms) into a very dilute carbonic acid dissolves rocks slowly and steadily and accelerates soil formation.

In biological perspective, biodeterioration (rock weathering) is the achievement stories of the organisms of algae, fungi and lichens that initiate life there. All they need is a substrate to attach and desirable environmental conditions such as temperature, moisture and light. The substrate refers to a special environment (rocks, stones, walls, glass, earth, crust, etc.) which lichens attach and live on, rather than a habitat. The nature of the substrate is efficient to some extent depending on the deterioration agents, for instance, in the case of nutritional requirements.

Degradation of organic materials is carried out especially by heterotrophic organisms, while the autotrophs are more capable for deterioration of inorganic materials. Therefore the ecological succession is owned by the autotrophs. Those photosynthetic organisms (algae, lichens and plants) demand a substrate for two purposes: a place of residence and beneficiation from minerals of it.

Limiting factors for biological growth include nature of the substrate; its pH, RH, aspect and orientation of the surface and its texture; patterns of water run-off; levels of nitrification (e.g. from bird droppings); light quality; and levels of atmospheric pollution that are consequently penetrative for biodeterioration of stones.

Carbon dioxide (CO_2) is released through respiration by all aerobic organisms. In the presence of water, it changes into a weak acid, carbonic acid (H_2CO_3) that reacts with the substrate. Carbonic acid can dissolve calcium and magnesium carbonates of limestone, marble, lime mortar, plaster, etc. and causes weathering of rocks (Caneva et al. 1991).

The most important form of biological degradation in the formation of cavities on the calcareous rocks, in terrestrial conditions, describes the impact of organisms such as fungi, blue-green algae, green algae and lichens growing on the surface of the rocks (Dannin 1992). The sphinxes and ruins covered by lichen populations in historical monuments in Alacahöyük in Turkey from the Hittite Empire Age (1450–1200 BC) was photographed by G. Özyiğitoğlu (Figs. 10.1 and 10.2) (Küçükkaya 2014).

In the case of colonization of biological organisms on monumental or historic stones, the degree of deterioration of whether it causes damage or not is a questionable phenomenon as well as determination of the methods for conservation.

The lichen *Dirina massiliensis* forma *sorediata* was mentioned as destructive agent on the monuments in Italy, Spain and Portugal over the last two decades (Seaward and Edwards 1995; Saiz-Jimenez 2001; Scheerer et al. 2009). As another study on biodeteriorative lichens, Uppadhyay et al. (2016) reported diversity and distribution of 28 lichen species from the monuments in Gwalior division in India. Sixteen species of lichens were identified growing on the surrounding walls of the Anadolu Fortress and the Rumelia Fortress in Istanbul which are exposed to anthropological impacts (Çobanoğlu et al. 2008a).

Recognizing biological deterioration and distinguishing it from other causes of destruction are possible with the understanding of the morphology of the

Fig. 10.1 Historical monuments in Alacahöyük in Çorum province (Turkey) are covered by the crustose lichen populations. The orange rosette-like crustose lichen is *Xanthoria elegans*; greyish rosettes are *Lecanora muralis*. (Photo by G. Özyiğitoğlu)

Fig. 10.2 Sphinxes and ruins in Alacahöyük, Çorum (Turkey), covered by orange crustose lichen – *Xanthoria elegans* – an example of stone that biological cavities have formed. Also *Lecanora muralis* (grey in rosette form) and other white crusts have been developed. (Photo by G. Özyiğitoğlu)

deterioration. Detailed taxonomical (position of organism's systematic level such as kingdom, division, class, order, genus, species and comparison with other groups) and biological (cell organization, tissue structure, physiology, growth forms, reproduction strategies, colouration, colonization patterns, habitat preferences, etc.) knowledge about organisms is required to be able to take precautions and/or be kept under control.

Biodeteriorative organisms, algal or fungal patinas, mosses and some lichens especially due to small sizes, are often confused with each other by nonbiologists. Individual species of the organisms that presumably attack monumental stones and derivatives can be best described by experienced specialists of each group.

10.2 Lichens as Ecological Values in Nature

The lichens in which members of 2–3 kingdoms live together are "self-sufficient miniature ecosystems" as Farrar (1976) describes in the lichen definition. From an ecological standpoint, they are extraordinary creatures that can be kept alive in very different ecosystems, ranging from the desert to the poles, adapting to extreme conditions in nature. With their exceptional abilities, they can develop in a wide geographic range in various habitats. Although they are durable to extreme conditions and live long, it is known that lichens grow very slowly and at the same time they show sensitivity to air pollution.

The natural habitat of lichens is mainly terrestrial. All lichens except the two aquatic species are continental life. These are one aquatic species *Peltigera hydrothyria* Miądl. and Lutzoni and one marine species *Verrucaria serpuloides* M. lamb. A few species of lichen live on the freshwater currents and on the coastline, which is affected by the tides of the seas. For example, there are many species such as *Caloplaca* and *Verrucaria* that live on the siliceous rocky shores of the sea, not in the sea. Some lichens grow on hard siliceous rocks in freshwaters, such as *Ephebe*, *Hymenelia*, etc. Apart from these, the majority of lichens are naturally distributed on substrata such as soil, rocks or trees in forest, hill or high mountainous terrains (alpine and tundra). Some species have even adapted to unconventional estates such as man-made buildings, walls, tiles and even concrete, plastic, glass and metal, belonging to natural urban and rural living environments.

There are two types of food sources for lichens. The "atmospheric sources" are precipitation, fog, dew, frost and air humidity. The second is "substrate sources". The nutrients of lichens living on soils and rocks are affected by the pH level of the environment in terms of solubility. Limestone contains more nutrients than acid rocks. The species of lichens that develop in these environments are also different. In addition, soil and rock species contain dust and soil particles flying around, where elements Al, Fe, Sc and Ti are present in high concentrations. They enter the intercellular spaces in lichen tissue. However, because the solubility of these substances is slow, lichens do not benefit as much as they need from dust. Epiphytic lichens are also affected by the characteristics of the tree bark and by the canopy. The nutrient composition of the bark also affects the pH level of the environment. The species of lichen on the neutral bark are different from those on the acid bark. Air pollution also affects the nutrient content of the tree bark and changes the lichen communities due to lowering pH with acid accumulation; calcium (Ca) accumulation causes the pH to increase, causing the lichen communities to change in the opposite direction (Nash 2008).

What are the environmental roles of the lichens in nature? The known ecological functions of the lichens in the nature, which will be elaborated in detail throughout this chapter, are summarized in the following items:

1. The lichens function as indicators for atmospheric pollution.
2. Lichens are pioneering organisms in succession and in soil formation.
3. Lichens help prevent erosion.
4. The role of lichens in the mineral cycle in ecosystems is great.
5. Lichens function as habitat for various fauna (birds, insects, invertebrates).
6. Lichens are a source of nutrients for some animals in the wild.
7. In the food pyramid in the ecology, the lichens are different from the other lichen-free fungi, not in the consumer's step, but in the producers' step by photobiont.

10.2.1 Lichen Biodiversity

The lichens among the terrestrial autotrophs on Earth are incredibly diverse in nature miniature. They have a fantastic range of colours: orange, yellow, red, green, grey, brown and black. Their size ranges from small 1 mm^2 dense lenses that are difficult to see to those with a length of 2 m, hanging from the branches. The largest foliose species is epiphytic *Lobaria pulmonaria* showing distribution in the old forests widespread in oceanic and montane Europe, and also in Macaronesia, North and South Africa, North America and Asia, but now extinct in the lowland plains of central Europe. The lichen species diversity is quite high in the old forests of mountainous areas with high altitudes, the rugged pebble ocean coastal cliffs and the tropics. For example, in Papua New Guinea, 173 lichen species have been reported on a single tree (Aptroot 2001). Species diversity grows with the diversity of ecosystems (Lohmus et al. 2007). The regions where the lichens develop best are tundra and high mountainous areas. Wherever the earth is – as slow-growing living creatures – they prefer robust rock surfaces with plenty of light. Oceanic coastal populations can have a rich lichen flora that is not seen elsewhere.

Lichens are colonies of bare soil and rock surfaces in addition to their presence on trees and other plants as corticolous (bark) or lignicolous (wood) epiphytic communities. The most prominent saxicolous communities on the rocks are epilithic on the surface, and others are endolithic in rock holes or cracks. Basic rocks such as limestone (high pH) and acid rocks (low pH) such as basalt often host different lichen species. Soil chemistry is also important for terrestrial communities living on the soil. In the tropics and subtropics, some fast-growing lichens colonize as epiphyllic communities on the surface of the leaves. In addition, some livestock lichens are colonizing some communities such as turtles and insects. In addition, there are microscopic aquatic invertebrate animals living on and between mosses and lichens.

Lichens live in most of the world's terrestrial ecosystems until they cover about 8% of the Earth's surface (Socthing 1999). However, biomass distributions vary widely. The majority of polar and subpolar ecosystems of lichens are dominant autotrophs. Lichens are a prominent element of many alpine, marine and forest ecosystems, such as the temperate rainforests of the Southern Hemisphere and the Northern Hemisphere. Because many lichens have relatively slow growth, their primary productivity distribution is quite small in most ecosystems. Ephemerals (annuals) are extremely rare among lichens. Lichens are "perennial" creatures that develop for many years. They grow very slowly and last very long. A crustose lichen species grows up to an average of 1 cm per year on average. By contrast, lichen varieties with leafy and flat thallus grow faster.

Another noteworthy point is that some lichens survive for 1000 years and are used to determine the age of rock surfaces. Growth can range from "invisible" to "several mm" per year. Faster-growing species can increase their biomass by 20–40% per year, and especially if they are the dominant species, they play an important role in the mineral cycle of the ecosystem they are in (Nash 2008).

10.2.2 Lichen Sociology

The various lichen communities separated by sociological analyses and other means also determine the significance of not only the diversity, frequency and biomass of different species but also their relation to the other components of the ecosystem or community, thus showing lichen-rich ecosystems.

Among the lichen species, various sociological units have been found to occur primarily within the broad vegetations that start with grouping in narrow areas due to substrate specificity and vary according to their geographical distribution. For these communities, sociological classifications are made with traditional phytosociological approaches or numerical approaches based on more recent statistical data analyses. In other words, associations determined by phytosociological approach and by floristic and intuitive methods can also be grouped as a result of numerical analysis of data obtained from random sampling techniques (James et al. 1977). The most appropriate is the comparative application of phytosociological and numerical approaches.

In the socioecological studies, epiphytic communities were uncovered, and even the keys were formed in accordance with the parameters such as canopy openness, tree type, crust feature (acid-basic, etc.) and tree diameter in the forest (Prigodina-Lukosiene and Naujalis 2001). There are also studies showing the distribution of lichen species associations with substrates such as natural or man-made stone residues, walls and rocks in habitats varying by the degree of exposure to haemerobic factors (human impact, urbanization, air pollution, etc.) (Lisci et al. 2002). Lichen species in a tree trunk may exhibit vertical propagation depending on microclimatic conditions. Çobanoğlu et al. (2008b) stated that the highest density of lichen species is between 16 and 18 m and that 11% of the species is above 6 m, with species density increasing between 4 and18 m in 27–37-m-long fir trees. The species distribution with 2 m intervals along the tree was observed, and some lichen species (*Bryoria fuscescens, Caloplaca herbidella, Cyphelium inquinans, Lecanora argentata, Ochrolechia androgyna, Pseudevernia furfuracea and Ramalina thrausta*) were reported to occur first 2 m above from ground, and about 47% of the species frequency occuring at above 4 m on the tree.

In some cases lichen species can also unite with mosses in the same environment (Sjögren 1988). In a study conducted by clustering analysis in Sweden (Bengtsson et al. 1988), it was observed that in the areas grouped by the habitat characteristic (siliceous, calcareous rocks or soils, limestone, coniferous or leaved forest types of forests, pastureland, etc.), algae and mosses formed by vegetation included in vegetation together with high plant communities.

Studies on lichen sociology are currently limited, and there is a need to increase these studies to better understand the ecology of lichens.

10.2.3 Ecological Factors Affecting Lichens

Lichens show susceptibility to climate changes (abiotic ecological factors) in general, as well as to changes in the chemistry of air, habitat and substrate (biotic ecological factors), as they feed on air.

In particular, the change in the concentration of elements and gases leading to atmospheric pollution negatively affects the likelihood of development. For this reason, the majority of lichen species are selective about habitat and substrate. In the case of contamination, there are differences in the colonization of lichen species in that region. The lichen composition of the region varies depending on the sensitivity of lichen species.

Environmental factors affecting the natural development of lichens are classified by Huckaby (1993) under the headings "macrohabitat" and "microhabitat" factors.

Macrohabitat factors:
1. Sunlight (the intensity and quality of the light is important, the light wavelength required for photosynthesis should be 460–640 nm)
2. Wind (speed and frequency)
3. Temperature (maximum, minimum, seasonal values)
4. Humidity (rain, snow, fog, annual average, minimum and maximum values)
5. The chemistry of atmospheric air (nutrients, toxins, acidity, and the type and proximity of pollution sources in the environment)

Microhabitat factors:
1. Substrate (topography, chemistry, stability, humidity and type such as rock, tree bark, moss, other plants, man-made materials)
2. Soil (structure and chemistry of soil is important, such as pH, toxins, nutrients, colour, particle size, water retention capacity, % rock content and % plant cover)
3. Atmospheric gases (concentration changes in, e.g. CO_2, ozone)
4. Forest cover (canopy). Percentage of openness of the top cover (% open area ratio) formed by tree branches and leaves that are shading in the forest

Most of the factors in this area are influenced not only in lichens but in different dimensions on many living beings around. Species choose their habitat according to whether these factors are suitable for their survival or to live there according to their ability to adapt to those conditions. In this context, ecological valences of lichens determine their tolerance limits. In addition, the impact ratings of ecological factors vary according to the lichen species.

10.3 The Environmental Roles of Lichens in Natural Ecosystems

10.3.1 Pioneers in Succession and in Soil Formation

Lichens living on bare rocks, which other creatures cannot hold, pioneer the formation of soil by slowly piercing and eroding the rocks with lichen acids they secrete. A thin soil layer formed over the rock will make possible growing of other lichens and mosses and so higher plants with the increase of organic matter.

The roles of the lichens in shaping the natural life are great. They can sustain life on bare rocks where no creature has ever existed before they can begin their first viability (primary succession). Saxicolous lichens provide soil formation by crumbling the rocks they hold with lichen acids they secrete, in a very long period of time. In this way, there they prepare suitable grounds for other living species such as mosses and higher plants. It enables the development of other species of lichens and mosses in the thin soil layer formed and higher plants with the continual increase of the organic matter. Likewise, in an environment that has previously been alive but has been damaged in some way, lichens can resume life (secondary succession). Thus, lichens are pioneer organisms that function both in primary succession and secondary succession.

10.3.2 Erosion Prevention Feature of Lichens

Terricolous (epigeic) lichens, such as tree roots, soil algae and mosses, are among the creatures that hold the earth and prevent it from slipping.

The foliose cyanolichen species such as *Collema*, *Leptogium* and *Peltigera*, as well as many other fruticose, crustose and squamulose soil lichen species such as *Cetraria* and *Cladonia*, catch and firmly grasp the soil particles by the hyphae of their mycobionts. Thus, lichens are among the erosion prevention organisms such as some soil algae, mosses and root crops.

10.3.3 Functions in the Mineral Cycles in Ecosystems

The organisms involved in the "nitrogen fixation" phenomenon, which means that nitrogen N_2 ($N \equiv N$) from the atmosphere is converted into ammonia (NH^{4+}), are only photosynthetic cyanobacteria and certain bacteria, so the nitrogen in the air becomes available for other plants as well (Sodhi and Ehrlich 2010). Cyanobacteria also maintain this function in the lichen. In this respect, cyanolichens also play an important role, especially in the atmospheric nitrogen cycle. For example, blackish colour *Collema* and *Leptogium* species, grey-brown *Peltigera* and green colour *Lobaria* species commonly found on the soil surface or on tree bark are among the cyanolichens in the foliose form, usually containing *Nostoc* as cyanobacterium. In ecosystems such as temperate rainforests and some subarctic ecosystems where cyanolichens are abundant, the nitrogen rate is remarkable.

The poikilohydric structure of lichens affects the hydrological cycle (water cycle) even in some systems where the biomass is small. In arctic and subarctic regions, lichens that constantly cover the ground can permanently saturate the soil (when not frozen) by preventing evaporation from the soil. Lichens, which are part of the cryptogamic crust commonly found in uncontaminated soils in arid and semiarid regions, facilitate the draining of water into soil in this layer. Even epiphytic lichens can change the hydrological cycle in ecosystems.

There is evidence that lichens may affect daily, monthly and seasonal mineral cycling. Changes in ecosystems affect N, P and S cycles (Sodhi and Ehrlich 2010). Al, As, Ca, Cd, Cu, Fe, Hg, Mn, Ni, Pb, Sc, Ti, V, Zn, N, P, S, C, O and H elements retained by the lichens and the compounds containing them, the accumulation of macro- and microelements in the thallus and the effects on the balance of ecosystems are still the subject of many studies.

10.3.4 Nutrient Source and Habitat for Fauna

For some animals, lichens are a food source with a critical prescription because it is very difficult for them to find plants in the winter. The nutritional requirements of animals such as deer, roe and squirrel vary according to season, age, sex and location. In this case, the lichens play life-saving role until autumn.

Cladonia stellaris is the most abundant lichen species, and the filamentous *Bryoria* and *Alectoria* species are also eaten by deer in boreal forests. *Cetraria islandica* and *Cladonia rangiferina* are the nutrients of reindeer. Reindeer and caribou take their soil lichens out of snow. Lichen *Alectoria sarmentosa* known as the witch's hair is an important source of nutrients for the black-tailed reindeer. Especially these deers and the other animals fed with lichens have special enzymes called "lichenase" for the digestion of lichens (Svihus and Holand 2000; Jewell and Lewis 1918).

Lobaria linita, foliose tree lichen, is eaten by mountain goats in Alaska. Lichen *Bryoria fremontii* with filamentous morphology is a food and nesting material for squirrels. The predominant winter food of flying squirrels is composed of *Bryoria* species (Rosenireter et al. 1997). The raised-nosed monkeys, endangered in China, are also fed by two species of *Bryoria*. Snails are also among the living things that are usually fed with lichen. It was also noted that spruce forest poultry and wild turkeys were fed with lichen (Sharnoff 1997).

A wide variety of invertebrates and many kinds of insects such as moths, butterflies and caterpillars including springtails (Collembola), barklice (Psocoptera), lacewings (Neuroptera) and moths (Lepidoptera) among the lichen thalli for feeding (Nash 2008) can be called "lichenivorous" (fed with lichen).

It is known that many mammalian species feed on lichens. Diets of deer, elk, aquarium, musk oxen, mountain goat, arctic pole, field falcons, tree falcons, mountain rats, squirrels, apes and some domestic animals may contain lichens as supplement or winter feed for normal diets (Seaward 2008).

In the food pyramid in the ecology, the lichens different from the other non-lichenized fungi are not in the consumer's step, but in the producers' step by photobiont. For this reason, lichens, which produce their own food by alga/cyanobacteria partners who can make photosynthesis, are the producers in the food chain. The decrease in the number of species of lichen group by pollution or other reasons in vegetation will affect other living groups. The damage of one of the circles in the food chain will harm human beings both directly and indirectly, by affecting the animals that feed on, use as nest, and other animals fed with it.

The thalli of fruticose and foliose lichens that develop on the rocks or in the crevices have nesting and hatching environments for various invertebrates and insects. For example, *Ramalina* species are nesting environment for lady bugs (*Coccinella septempunctata*), photographed from Turkey (Fig. 10.3).

Some foliose and fruticose lichen species are birds' nesting material, for example, *Parmelia sulcata* as nest material of common finch bird *Fringilla coelebs* (Karabulut and John 2006), photographed in the province of Çanakkale in Turkey (Fig. 10.4), and humming birds that nest with the foliose *Lobaria pulmonaria* the so-called lung lichen. Some birds utilize the white lichen, *Thamnolia vermicularis*, which grows on

Fig. 10.3 *Ramalina* lichens on rock as nesting environment for lady bugs. (Photo by F. Atak)

Fig. 10.4 Bird nest made of foliose lichen *Parmelia sulcata.* (Photo by Ş.N. Karabulut)

the soil, for the construction of nests. The weaver's bird seems to have made its nest completely out of *Usnea* species.

Besides the fact that lichens are hatchlings for invertebrate animals, the loss of this important nutrient source also affects complex food webs where bird populations are dependent. Many bird species use lichens as nest materials, while others prefer certain lichen species with camouflage and decorative purposes at the same time. It is difficult for them to distinguish from the environment with entangled entities, but they become evident when they move. Flying squirrels (*Glaucomys sabrinus*) are highly selective in the selection of lichen material; they use in particular three species of *Bryoria* as nesting material (Rosenireter et al. 1997).

10.3.5 Bioindicators for Atmospheric Pollution

Since this is not a waterproof protective layer like chitin, lichens take directly all the pollutants in the air such as sulphur dioxide, metals, radioactive substances and so on and accumulate them in their thallus. For this reason, they exhibit susceptibility to atmospheric origin contaminants, especially at levels varying by species especially those with large surface areas. Except for some durable crustose species, susceptible lichen species exposed to haemerobic impacts in an area show biological deterioration and gradually begin to fade away. Thus the lichen of that zone shows the level of air pollution. The use of lichens as a biological indicator for air quality is a well-known approach for a long time.

10.3.6 Lichens in Biodegradation Events

Many living organisms in different biological structures, such as algae (blue-green, green, golden yellow, red, brown or black), bryophytes, lichens, bacteria and some fungi are among the organisms that develop on the rocks in general (Küçükkaya 2014). It is known that these organisms lead to the perforation, crumbling and disintegration of the rock over time, that is, they are worn out from the surface, which is called "biological destruction" or biodegradation, that is, "biodeterioration".

Appropriate climatic factors (temperature, humidity, rain, sun exposure or glare, inorganic and organic pollutants) and even optimal environmental conditions can be found on the surface of stone structures (aesthetic damage) and sometimes deeper (physical and chemical damage) for the development of organisms. Macroscopic organisms such as epilithic microorganisms (cyanobacteria, bacteria, various algae, mould fungi, etc.) and birds, some insects, plant roots, bryophytes and lichens are living groups responsible for biodeterioration (Scheerer et al. 2009). Each has different aesthetic, physical or chemical effects.

Lichens trigger physical and chemical damage because lichen acids can make the substrate soluble and break down (Caneva et al. 1991). One of the most obvious effects of lichens is the formation of pits or holes. In addition, lichens enrich the organic matter on the rock surface and form a thin layer of soil, allowing higher plants to develop here.

One of the important ecological features of lichens is their acidic properties, which they secrete, to form pits on the rocks and provide soil formation over time. For this reason, lichens are among the organisms causing biodegradation. As they are natural rocks, man-made stone structures (historical monuments, buildings, etc.) also cause consequent changes and deterioration of chemical and physical events (St Clair and Seaward 2004). By dissolving carbon dioxide released from lichenin respiration, holes are formed on the stone, and the crumbling occurs. When compared with this natural phenomenon occurring on the geological time scale, it can be considered that the effect of biodegradation is weak since the historical process is not very long. However, the role of biological destruction in architectural stones is important. It is an important issue to protect the historical rocks, sculptures, cultural and architectural value of stone works without biodeterioration. If these organisms are not required to colonize the organisms, techniques should be used to prevent them. Care should be taken to ensure that the surfaces covered by the biological organisms are cleaned so that no more species are destroyed as the stone is not damaged.

10.4 Biodeterioration and Biodeteriorative Organisms

From the definition of deterioration, which means loss of structural capacity over time due to external factors or material weakening, a description of "biodeterioration" was specified by Hueck (1968) as "any undesirable change in the properties of a material caused by the vital activities of organisms". In the same way, Rose (1981)

Table 10.1 Groups of biodeteriorative organisms growing on rocks

Prokaryotic organisms	Eukaryotic organisms
Bacteria	Algae
Cyanobacteria (blue-green algae)	Fungi
	Lichens
	Mosses
	Plants
	Animals

defines biodeterioration as the process by which biological agents are the cause of reduced structural quality or value.

Biodeterioration and biodegradation terms are often misused in place of each other. As stated by Allsopp et al. (2004), biodegradation relates to the use of microorganisms to modify materials according to a favourable or beneficial purpose, whereas "biodeterioration" is attributed to the negative effect of living organism activity. Biodegradation refers to the disintegration of materials by bacteria, fungi or other biological means. The term is often used in relation to sewage treatment, to environmental remediation (bioremediation) and to plastic materials.

Biodeterioration is classified into three categories (Gaylarde et al. 2003). These processes may occur separately or at the same time depending on the "biodeteriogens", the structure of the material and the environmental conditions.

1. Physical or mechanical
2. Aesthetic (fouling or soiling)
3. Chemical (assimilatory and dissimilatory)

The living organisms most commonly associated with biodeterioration of construction materials, biodeteriogens, are grouped as below (Sanchez-Silva et al. 2008):

1. Marine borers (e.g. gribble and shipworms)
2. Insects (e.g. termites and wood-boring beetles)
3. Fungi (moulds), algae, lichens
4. Microorganisms (bacteria, cyanobacteria)

The living organisms causing biological deterioration on rocks are indicated in Table 10.1. The general properties of each group were comparatively summarized under the following headings (Küçükkaya 2014).

10.4.1 Bacteria (*Bacteria, Cyanobacteria*)

Bacteria are single-celled organisms or are cells into colonies characteristically associated in chains or clusters. A bacterial cell in various shapes, small enough to be seen only under a microscope (1–10 microns), cannot be seen visually. Bacterial cells often form closely aggregated mats called biofilms to attach to surfaces. Bacteria within biofilms are more protected and it is much more difficult to eliminate.

Cyanobacteria known as blue-green algae are photosynthetic and aquatic organisms which also take place in the kingdom *Bacteria*.

Bacteria and blue-green algae (*Cyanobacteria*) are the most simple and small-celled organisms. Another important common feature of these two groups is they have prokaryotic cells. For this reason, bacteria are considered more primitive; all living things except this group are eukaryotes.

Cyanobacteria bear the name "blue-green algae" due to the blue pigment phycocyanin. Also, they contain the green pigment chlorophyll, like other algae, and so are photosynthetic bacteria with blue-green colours. Most of the other bacteria having no chlorophyll cannot make photosynthesis. They produce their own food through chemosynthesis using inorganic sources such as sulphur, methane and nitrogen. Most of the bacteria live in other cells as parasites and some are pathogenic causing disease.

A slippery greenish or blackish trace is formed on stone surfaces when colonized by cyanobacteria (e.g. *Gloeocapsa*, *Nostoc* and *Oscillatoria*).

There are three types of bacteria known to live on the stones (sulphate, nitrate, heterotrophic) (Fig. 10.5).

Sulphate bacteria (sulphur oxide bacteria), decomposing white lead $PbCO_3Pb(OH)_2$ often formed by a combination of lead carbonate and lead hydroxide by chemical way, cause to occur black-coloured PbS in the region. This way the surface colour turns to grey. Sulphate bacteria can be identified in this way. Gypsum,

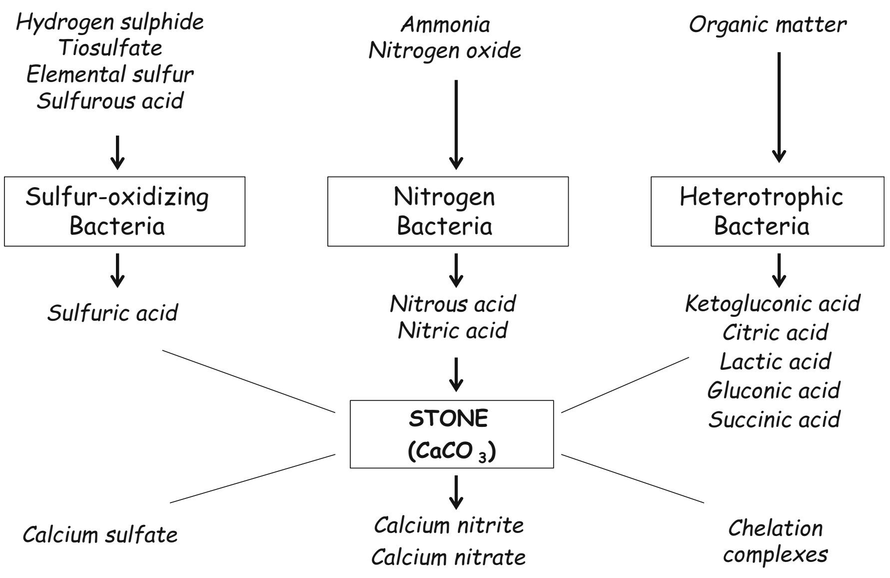

Fig. 10.5 The action scheme for bacteria living on stone (Caneva et al. 1991)

causing superficial and structural degradation of limestone, may be a typical reaction of sulphur oxide bacteria especially of "*Thiobacillus*" type in dirty air (Alexopoulos and Mims 1979).

10.4.2 Algae (Algae or Seaweeds)

Algae, commonly known as "seaweeds", single-celled or in colonies of microscopic forms or multicellular filamentous or leafy macroscopic forms up to several metres in size, are the photosynthetic organisms like plants, whose body is termed a thallus (no organs such as leaves, stems and roots but a whole body). Algae have green, golden yellow, red and brown colours due to consisting of different pigments, which is one of the most particular criteria for their classification. They are separated into various classes located in the kingdom Protista. There are thousands of algae species in sea or freshwater and on land, living in damp habitats such as rock faces, tree trunks and soil. A few even live endolithically within the pores of rocks in deserts, relying upon night-time dew for their source of moisture. Algae have a worldwide distribution and are prominent in bodies of water and common in terrestrial environments and are found in unusual environments, such as on snow and on ice. Some species of green algae "Chlorophyta" (*Trebouxia*) and blue-green algae "*Cyanobacteria*" (usually *Nostoc*) can establish a unique symbiotic life (common life of two or more species of organisms) with species of certain groups of fungi that participate in the internal structure of lichens. Organism of lichen is now not similar to the fungus or the alga consisted inside and is different in physiological structure as well as in the outer appearance. Since both groups of lichen-forming algae have green pigment "chlorophyll", this provides the necessary nutrients to lichen by photosynthesis.

The algae on land are often pioneer organisms as well as lichens growing on bare rock (if the moisture is enough to survive). The rock weathers and crumbles, the algae die, and the remains of both contribute to formation of soil. This leading activity opens the way for more demanding plants to invade.

Algae colonize ledges and projections, cracks and crevices and areas of water run-off. One key characteristic of algal colonization is that they rarely exhibit any sharp boundaries. A further distinguishing feature is that the most commonly encountered species group of algae are a distinctive yellow-green colour (sometimes orange).

According to a review on colonization of algae that causes deterioration of cultural heritage in European countries of the Mediterranean Basin, about 172 taxa of *Cyanobacteria* and Chlorophyta (green algae) were reported in 32 analysed papers. The most commonly mentioned taxa among the *Cyanobacteria* are *Gloeocapsa*, *Phormidium* and *Chroococcus*; and among Chlorophyta are *Chlorella*, *Stichococcus* and *Chlorococcum* (Macedo et al. 2009).

10.4.3 Fungi (*Fungi*)

Fungi having some characteristics in common with both plants and animals are examined under a separate kingdom (*Fungi*). They are made up of colourless cells called "hyphae" lacking chlorophyll and avoid carrying out photosynthesis. Some of the mushrooms (*Basidiomycota*) may contain coloured pigments. They have cell walls like plants but consisting of "chitin" as a main component instead of cellulose. Fungi having about 60,000 species live in water or on land saprophytic or parasitic on animals and plants. Members of the group of *Ascomycota* are mould-forming fungi (a mass of hyphae called mycelium) and the yeasts. The moulds occur in different coloured blots such as black, white or brownish on shaded surfaces of stones and other habitats with enough moisture.

Fungi may have a mutualistic association (life association in which both of the partner species benefit from each other) with plant roots forming mycorrhizae occurring on roots of about 95% of all seed plants. They are probably essential to the survival in nature of both partners. The plant derives an enhanced ability to absorb essential minerals and greater resistance to root diseases. The fungus obtains sugars directly from its partner, without competition from other microorganisms.

Specific groups of the fungi (frequently *Ascomycota* and some *Basidiomycota*) come together with green algae and/or blue-green algae in another mutualistic symbiotic association with the form of lichens. Fungi inside the lichen thallus can be observed only under the microscope. They are involved in sexual reproduction of lichens via their spores. In addition, surrounding algal cells with their hyphae, they participate in producing vegetative reproductive structures of lichens. By wrapping algal cells with their hyphae, fungi provide a humid environment for algae, and so external influences and likely desiccation of algae are preserved. When algal and fungal cells come together, they begin to produce lichen substances, and they create a variety of colours, and a new live view of both of them is different, in a lichenized fungi.

As well as bacteria, algae and lichens, fungal activity initiates pitting corrosion on reinforced concrete structures with time (Sanchez-Silva et al. 2008). Fungi may participate in biodeterioration process on stone monuments or works of art by either itself as a fungus species (such as *Cladosporium herbarum*, *Aspergillus niger* and *Penicillium* sp., frequently with dark spots) or involving in the thallus of a lichen species.

10.4.4 Lichens

Lichens are organisms that live on a variety of substrates such as rocks, stones, bricks, soil, tree bark and wood and are usually miscalled "mosses" among the people. Patterns of many lichen species come together to form different coloured and shaped spots on rocks. Biological structure consists of the algae (*Cyanobacteria* and Chlorophyta) which is located together often with the fungi of an *Ascomycete* (or rarely a *Basidiomycete*, especially in tropical regions) in one body "thallus".

Lichens unlike mosses have white, black, orange, green, red, yellow, brown and a variety of colours and hard and brittle structure. They sometimes thrive together with mosses side by side or on. General appearances are mainly separated into the thallus types: crustose (appears crust-like and attaches to substrate very tightly), foliose (a leaf-like thallus that attaches to substrate by rhizines, root-like extensions underside of the thallus), fruticose (attaches to substrate at one point and appears shrub-like or filament-like), squamulose (scale-like thallus that appears in between crustose and foliose, attaches to substrate in one or more points underside) and leprose (a granular or powdery form of the crustose thallus) (Figs. 10.6, 10.7, and 10.8). Leprose lichens are sometimes difficult to be distinguished by the naked eye from algae on rocks or on tree trunks. Algae have more powdery (fine) structure, while leprose lichens have more granular appearance.

The poikilohydric (being able to live in environments with variable water levels) characteristic of lichens makes them survive in extraordinary habitats (Hashton 2000). Since they are resistant to water stress, there are species capable of living in environments ranging from deserts to the poles.

The lichens represented with about 20,000 species on earth grow very slowly. Development of lichens to a visible diameter of up to several centimetres in the form of a rosette takes more than 50 years. The slow development among lichens is probably due to their ability to continue respiration but stop photosynthesis and keep themselves in a kind of dormancy state under drought conditions (Nash 2008). Therefore they can stay alive on old stones for many centuries. Moreover, it is possible to establish the date of elements of historic buildings, by following the annual rates of growth of lichen species and the ones on undated substrata colonized by the same species (Fig. 10.9).

Lichens have an important ability on colonizing a life union (symbiosis) together with at least two species (sometimes triple symbiosis in one thallus). One of the partners is an alga belonging to Chlorophyta and/or *Cyanobacteria*, and the other is a fungus often from *Ascomycetes*. They usually colonize on a substrate in a few years. Lichens which grow on rocks and stones, including man-made rock derivatives such as wall, concrete, marble, stone monuments and works of art, are called "saxicolous". They usually prefer stable stones for colonization. The growth forms of thalli that colonize stone may be epilithic (on the outer surface of rock) or endolithic (inside the rock, within holes or cracks) (Lisci et al. 2002). Epilithic ones may occur

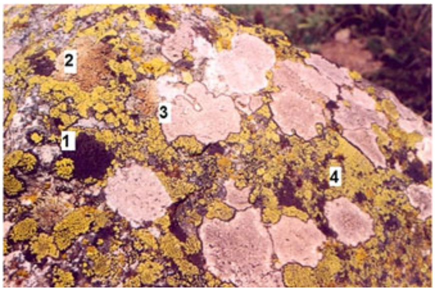

Fig. 10.6 Various lichens on a siliceous rock; *1. Xanthoparmelia* (very dark brown foliose), *2. Lecanora muralis*, *3. Pertusaria* sp. (grey crustose) and *4. Rhizocarpon geographicum* (yellow-black crustose). (Photo by G. Özyiğitoğlu)

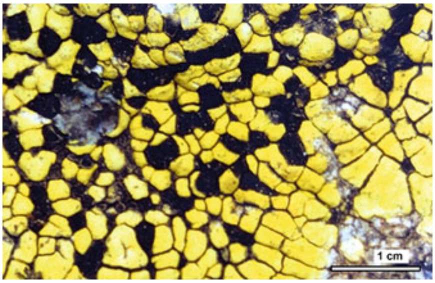

Fig. 10.7 A magnified photograph (under stereomicroscope) of the crustose lichen *Rhizocarpon geographicum* (yellow thallus with black spore-producing parts) on a siliceous rock (Photo by G. Özyiğitoğlu)

Fig. 10.8 An example of foliose lichen, *Parmelia* attach to substrate tightly by rhizines. (Photo by G. Özyiğitoğlu)

Fig. 10.9 A quite large (60-cm-diameter) and old lichen *Lobothallia radiosa*, growing radially on siliceous rocks. (Photo by G. Özyiğitoğlu)

in several morphological forms of crustose, leprose, squamulose, foliose and fruticose. On lower surfaces, the crustose lichens penetrate into the rock with their fungal hyphae. It is almost impossible to leave it from the surface otherwise scraping. The foliose lichens are also effective with their root-like extensions called rhizines under the thallus to attach to the substrate into the depth of about a few millimetres (Fig. 10.10).

The squamulose lichens attach to rock usually with hapter-like organs in one or more points. The fruticose lichens attach to the substrate on one point and usually hang down. Endolithic lichens, on the other hand, grow inside the rock totally or in part and often appear like a hole (Caneva et al. 1991) (Fig. 10.11). Observation of thin sections from lichen-invaded rocks under stereo microscope indicates size of penetration of fungal hyphae or rhizines. Species such as *Caloplaca crenularia*, *Candelariella vitellina* and endolithic *Verrucaria* spp. have shorter hyphae up to

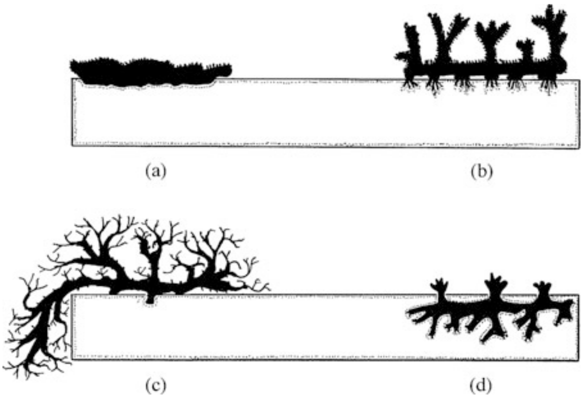

Fig. 10.10 Different forms of lichen growth on stone: (**a**) crust-like lichen; (**b**) foliose lichen; (**c**) fruticose lichen; (**d**) endolithic lichen (Lisci et al. 2002)

Fig. 10.11 An example of endolithic crustose lichen – *Verrucaria muralis* – growing on limestone. (Photo by G. Özyiğitoğlu)

1.5–2 mm in sandstones than *Lecidea fuscoatra* with 4–5 mm in volcanic clastites (St Clair and Seaward 2004).

Lichens produce lichen acids (more than 1000 secondary metabolites unique to lichens) all of which are of fungal origin (Nash 2008). Most of the lichen acids have a relatively low solubility, but they are effective chelators (that can form metal complexes effective in chemical biodeterioration), forming metal complexes with silicates, etc., derived from the substratum (Seaward 2003). Oxalic acid is a strong chelating agent and produced by fungi, lichens and higher plants (Caneva et al. 1991).

As a result of metabolic activity of mycobiont component (fungi), calcium oxalate (CaC_2O_4) crystals are deposited in some lichen species. Oxalic acid ($H_2C_2O_4$) which is extremely soluble in water and acts as a chelator of metal ions forming oxalates (Mg-oxalate, Ca-oxalate or Cu-oxalate) at the thallus/substrate interface is more active than the organic acids (Seaward 2003). Ca-oxalate is more common in lichens; however, all lichens cannot be generalized that produce oxalic acid. Products of lichens generally increase with age and are higher on calcareous rocks than on siliceous rocks.

The saxicolous lichens releasing carbonic acid (H_2CO_3) in considerable amounts cause fine detritions of rocks (Dannin 1992). Intensive cavities are formed on the surfaces covered by lichens as two types: mesopits and micropits (5–10 μm in diameter). Lichen penetrates into depths of 4–5 mm by their hyphae within mortar.

Depending on microclimatic conditions, species of lichens differ on the walls (Arino and Cesareo 1996). A different chemical composition occurs on weathered rocks compared to lichen-free substrates. Additionally, nature of weathered substrate differs according to biodeteriogen species. For instance, Erginal and Öztürk (2009) report more amounts of Fe and S and lesser K and Ca beneath *Xanthoria calcicola* compared to *Diploschistes scruposus* on the same rock.

Chemical mechanism of lichen weathering can be summarized by the following reactions:

1. Deterioration of $CaCO_3$ and $MgCO_3$ through carbonic acid from respiration in two steps
   (1) $CO_2 + H_20 \rightarrow H_2CO_3$ (carbonic acid)
   (2) $CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2$
   or $MgCO_3 + H_2CO_3 \rightarrow Mg(HCO_3)_2$
2. Acidic polysaccharides extracting metal ions
3. Oxalic acid, formation of two mineral forms of calcium oxalate (CO), the monohydrated whewellite (COM) and the dihydrated weddellite (COD) (Giordani et al. 2003)
   $Ca(C_2O_4) \bullet H_2O$ (whewellite = monohydrated form of oxalic acid)
   $Ca(C_2O_4) \bullet 2(H_2O)$ (weddellite = dihydrated form of oxalic acid)
4. Organic acids (lichen acids), chelating agents forming mineral complexes.

Effects of climatic change on lichens colonizing cultural heritage stone materials have been overtaken by their adaptive strategies (Arino et al. 2010). Some lichens benefiting from various adaptation strategies such as endolithic thalli development and thick and strong pigmented thalli are well adapted to dry areas with abundant sunlight; on the contrary they develop leprose or microfruticulose thalli by disabling the unnecessary cortex layer when growing on damp and shaded walls.

Lichens are pioneer organisms in ecological succession initiating life on a bare rock. Secreting their specific lichen acids, lichens attach to the rock and crumble it slowly and play a primer role in the soil formation. A thin layer of soil formed on rock allows the development of other lichens and mosses, and continually growing organic matter on rock enables continuous increase in the development of higher plants over time (Nash 2008). One of the most prominent effects of lichens is the formation of pits or crater-shaped holes especially on limestone and calcareous rocks, due to the lichen acids that have solubilizing and disintegrative action on the constituents (Prieto et al. 1997).

Lichens cause direct and indirect weathering of masonry, including gravestones, and often interfere with the legibility of inscriptions. On the other hand, in many countries, lichens are protected by the government and recognized as having equal status to monument conservation.

In the past, attention was drawn to the possible effect of dissolved carbon dioxide, derived from lichen respiration, attacking the substratum to produce pits and channels for easier penetration of hyphae. This is important on a geological time-scale, however, have so far been considered to be minimal in terms of the life of stone buildings and monuments. Seaward (2003) reports that many lichen species create microclimatic effects at the thallus/substratum interface, particularly in terms of water retention, which lead to mechanical damage to stonework on a short timescale of 10 or so years. Furthermore, forces generated by climatic wetting and drying of lichen thalli cause them to expand and contract in conjunction with the chemical breakdown of substrata by lichen acids.

Another well-known ecological feature of lichens is the bioindicator roles of certain species for level of air pollution (SO_2 and other pollutants). They accumulate heavy metals and radioactive materials from the atmosphere by their thallus surfaces (Garty 2001). According to the degree of their sensitivity to air pollution in a region while certain species are eliminated other species are colonized.

The lichen floras vary considerably according to the spatial differences in the chemical properties of stone surfaces, the microenvironmental conditions and the overall influence of air pollution. Changes in air pollution levels cause rapid disappearance of other more sensitive species and alternation in the composition of organisms with less sensitive lichens and other microorganisms. There is a direct correlation between the composition of the flora and the passage of time (Fig. 10.12). The diversity of the lichen flora can be a reliable indication of the level of air pollution which in itself is one of the most serious factors in the deterioration of ancient monuments (Seaward 2003).

Examples of lichen species on ancient monuments in the literature include *Tephromela atra* and *Ochrolechia parella* that are reported among the most abundant lichens colonizing granitic monuments in the region of Galicia (northwest Spain) (Prieto et al. 1997). Sixteen species of lichens were reported growing on the surrounding walls of the Anadolu Fortress and the Rumelia Fortress in Istanbul which are exposed to anthropological impacts by Çobanoğlu et al. (2008a) (Fig. 10.13).

The lichen diversity reported by Uppadhyay et al. (2016) from the monuments in Gwalior division in India are members of the lichen families *Physciaceae*, *Teloschistaceae*, *Verrucariaceae*, *Peltulaceae* and *Lecanoraceae*, respectively, according to species majority. According to morphological types, the most dominant lichen species are crustose species, which are followed by squamulose and foliose ones. The substrata types in various monuments are sandstone, concrete, igneous granite, calcareous and clay.

10.4.5 Mosses (Bryophytes)

Mosses (bryophytes) including liverworts, hornworts and true mosses (95%) are positioned systematically in the plant kingdom. From primitive to advanced order, they are more developed than fungi and lichens but more primitive than the ferns and the vascular plants. Since they contain chlorophyll they are able to make photosynthesis.

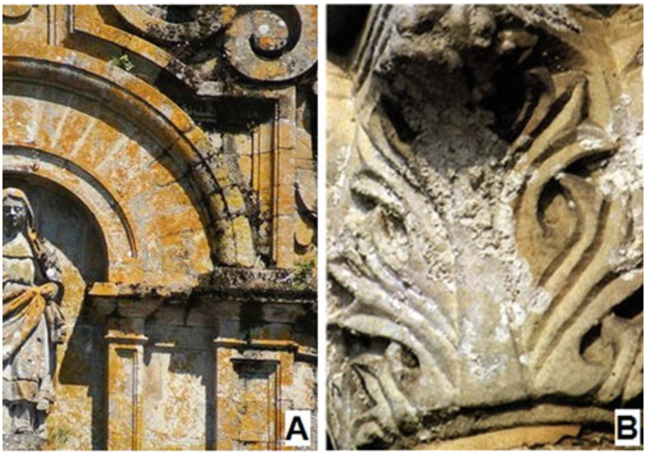

Fig. 10.12 Yellow *Caloplaca* species and diversity of other crustose lichens on the walls of Santiago cathedral in Spain (**a**), photo by H. Sengun. White crusts are *Dirina massiliensis* f. *sorediata* with large amounts of calcium oxalates (**b**) (Nimis et al. 1992)

Fig. 10.13 *Caloplaca flavescens* – one of the lichens on the bottom walls of the Anadolu Fortress in Istanbul (Çobanoğlu et al. 2008a)

Bryophytes, in most recent analyses, are classified into the Marchantiophyta (liverworts), Anthocerotophyta (hornworts) and Bryophyta (mosses). The mosses, unlike the liverworts and hornworts, are present in more terrestrial habitats.

Bryophytes carry all of the organs: leaf, stem and root-like (rhizoids) structures similar to higher plants. They (represented with approximately 26,000 species) live on moist and shady rock, soil and tree trunk appearing green to brown in colour. They can easily be removed from the substrate and so differ from some lichens that stick tight to the substrate with their entire lower surface.

Mosses as biodeteriogens form a green to brown layer depending upon species, much thicker than algal or fungal traces and softer than do crustose lichens on stones; they appear like lowered plants when moist but patches more crusty and darker when dry. They can be easily identified from the presence of leaves and stems with a magnifying glass or even by the naked eye (Fig. 10.14).

Fig. 10.14 Lichens (white-grey patches), mosses (green) and higher plants which are more apparent in winter with the increasing humidity on the calcareous garden walls in Edirne Beyazit Camii (mosque). (Photo by G. Küçükkaya)

Mosses and lichens are macroscopically evident because they cover the material surfaces with visible films of growth. Consequently, an aesthetic alteration is initially noticed (Prieto et al. 1997).

Concisely, algae, lichens and mosses are spore-reproducing multicelled photosynthetic land crops that form a visible microflora on similar habitats. On the other hand, traces or biofilms of bacteria, fungi and some microscopic algae are more difficult to be identified by the naked eye.

10.4.6 Higher Plants and Animals

The roots of trees can grow toward the water they need to live. If necessary, cracking the building blocks can reach water sources (Hashton 2000). Shrubs and trees, especially beech tree with its thick roots, are very dangerous for ancient stones. Even if damages are discussed, the vines, to some researchers, climbing plants were said harmless (Kieslinger 1968).

Lichens and mosses led the process of soil formation on the rock; organic matter gradually increases (Owen and Chiras 1990). Plant seeds coming with wind cling to this environment and develop roots. As roots enter into rock and thickens slowly, deformation increases (Fig. 10.15).

Higher vegetation growing on historical buildings and ruins includes plants such as herbaceous annual *Sonchus tenerrimus* and perennials *Centranthus ruber*, *Parietaria diffusa* and *Sedum pachyphyllum* and trees *Ailanthus altissima* (Lisci et al. 2002). Among the most frequent plants which cause mechanical force and/or chemical damage to stones are *Antirrhinum* spp. (herbaceous), *Capparis spinosa* (shrub), *Ficus carica* (shrub) and *Hedera helix* (shrub) (Caneva et al. 1991).

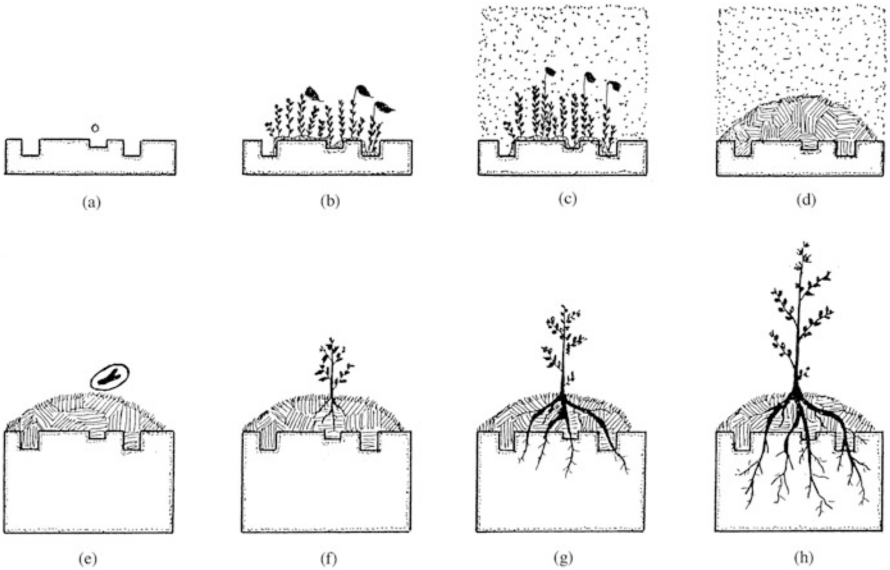

Fig. 10.15 The stages of a second mode of wall colonization. A moss spore (**a**) falls on porous stone, such as travertine, and develops (**b**). Atmospheric dust collects on the moss (**c**) forming a small amount of substrate (**d**). A seed falls on the substrate (**e**), germinates (**f**), grows (**g**) and flowers (**h**). The moss does not damage the substrate but the plant roots penetrate it. (Lisci et al. 2002)

Fig. 10.16 Plants growing on a bridge in Vatican. (Photo by L. Coşan)

Abandoned archaeological sites, particularly in warm tropical or semi-tropical regions, are occupied by plants quickly and are subjected to irreparable damage in a very short time. Small quantities of fragments of earth, moved with the wind, are stored over the archaeological remains. Lack of care is sufficient for the growth of the plants there (Fig. 10.16).

Removing plants and trees at first is the logical solution. Grass should be cleaned regularly throughout the year. If delayed (e.g. if plants established or roots developed well), intended to be difficult and hard to remove plants may cause damage on structures through mechanical cleaning. Especially when thick roots of woody plants penetrate into the walls, taking into account plants uprooted would damage the stone, the plants can be cleaned by cutting. But the growth occurs again. Therefore, the solution is not to cut or remove the roots, rather they should be eliminated by injecting poison.

Herbicides for wild plants are not toxic to human and animals, will not damage agricultural products, do not kill plants in and around the historic surroundings and do not cause chemical or physical damage to the stones. There is a wide field of use of this kind of products. These are neutral triazine compounds and are used as two types, absorbing only roots (chlorotriazines) and absorbing roots and leaves (methoxytriazines). The first type of plant killers is well adapted to both fine-leaved and broad-leaved herbaceous plants. None of triazines penetrate easily into the soil so that reduces the risk of contamination. Effects on plants starts 60 days after the application, and the application is made, in appropriate seasons, especially in spring and autumn periods (Lazzarini and Tabasso 1990).

As for the animals, pigeons living in large masses in the cities should be mentioned. Pigeon droppings with 2% phosphoric acid cover the architectural details in a bad way. Coverings of cornices made of forged metal, copper and zinc are disrupted and pierced. The rain from these goes into the stone walls and wets out and thereby indirectly causes destruction. Even seemingly harmless flies cause destruction, both with their waste left and with holes created by taking some chemical substances on the stone to be fed (Fig. 10.17).

In the case of historical monuments, molluscs (snails), insects and spiders, mussels, clams and sea urchins may be also deteriorative by chemical action of secreted acids and mechanical stress (Caneva et al. 1991). Reactions of all the mentioned biological organisms on different works of art are indicated comprehensively in the Table 10.2.

10.5 Management and Conservation Strategies

When physico-chemical and environmental conditions of a work of art accommodate with the character of the organism's genetics, biological damage can occur (Caneva et al. 1991). If the formation of conditions is prevented, the protection of the material is possible. Conservation methods are indirect methods. The aim is to

Fig. 10.17 Istanbul New Mosque (Yeni Camii)-Hünkar Kasrı, destruction and pollution caused by pigeons. (Photo by G. Küçükkaya (2014))

Table 10.2 Reactions of biological organisms on different works of art

	Stone	Glass	Metal
Autotrophic bacteria	Black crust, black-brown patinas, exfoliation, powdering	Pitting, opacification, black spots, blackened water-logged material	Corrosions
Heterotrophic bacteria	Black crust, black patinas, exfoliation, colour change	Pitting, opacification, black spots, blackened water-logged material	Corrosion
Actinomycetes	Whitish grey powder, patinas, white efflorescence	ND	ND
Fungi	Coloured stains and patches, exfoliation, pitting	Opacification, black spots	ND
Algae	Patinas and sheets of various colours and consistency	ND	ND
Lichens	Crusts, patches, pitting	ND	ND
Mosses	Green-grey covering surface layers	ND	ND
Higher plants	Grass, shrubs and woody species induce cracks, collapse, detachment of materials	ND	ND
Animals			
Marine borers and snails	Holes of typical shape	ND	ND
Birds	Deposition of excrement with corrosive effects, holes, scratches		

ND not described because they do not play an active role on these materials (Caneva et al. 1991)

prevent the development or slow down the surviving conditions for the organism by changing the values of the physico-chemical and biological environmental conditions of work of art if possible (Figs. 10.18 and 10.19).

Among the approaches, Tiano (2016) suggested the biogeomorphology theory as one factor to remove and prevent biological settlements. They proposed a model "Management of Dynamic Durability Model" describing the stone durability concept involving the biodeterioration process.

A close relationship and dependence of biological activity with the environment describes the limiting factors for the most effective method of preventing undesirable developments. Environmental factors cannot be changed all the time but can be changed only in the controlled areas such as museums. Biological destruction at the archaeological sites and the external surfaces of buildings is much more difficult to control. The parameters that can be changed in theory are humidity (Rh and the amount of water contained in the work), temperature and light. It is not possible to change inherent factors supplying these values without disturbing the structure of the work. However, nutritive factors that are not associated with the structure can be reduced (dust, pigeon manure, organic-based, improper restoration materials, etc.).

Fig. 10.18 Dissolution of the superficial surface and exfoliation (detachment) likely to be caused by microorganisms coating on (LRMH 2000)

Fig. 10.19 Chemical dissolution and regional contamination caused probably by the microorganisms viable on shady parts (LRMH 2000)

In places such as museums, libraries, warehouses and churches, factors that led to the development of biological organisms are:

- High relative humidity
- High temperature
- Poor ventilation
- Strong light
- Work containing organic material
- Dust, dirt and materials subsequently added to the restoration

All of these factors can be checked by a continuous care with simple or complex methods such as a complete air conditioning system.

High humidity is the main factor of biological attack that causes increase in development of microorganisms creating biological degradation. Temperature should be kept below 20 °C, 20–16 °C, but should not be forgotten that low heat slows down biological development, not completely avoids. Heat is not a limiting factor. The following measures can be taken, depending on the source of intense humidity: isolation against rising moisture, roof repair, proper water drainage system against leakage of water from the ceiling and the air conditioning to control excess heat. In tropical areas, thick protective walls and roofs or exterior corridors in parallel to artefacts rooms are additional solutions for new buildings. In cold climate regions, heating is essential. Materials can be placed in display cases in small ethnographic museum artefacts. Excess moisture can be absorbed with hygroscopic materials. The silica gel can be used for protection but has a limited capacity and should be replaced when frayed.

To control microclimate is very difficult in indoor places with a high Rh such as caves, tombs or outdoor spaces for public use. The visitors increase heat and humidity. Another indirect adverse effect is due to closing and opening the doors and turning on and off the lights by the visitors. In this case, average values are examined, and the protection requirements are created. If humidity conditions are appropriate, light and inorganic materials also help the development of microorganisms with photosynthesis. For example, in the burial chambers, mosses are numerous, and wall Rh and water levels are high. Since it is difficult to control the temperature and humidity in such places, a single factor to control and reduce the occurrence of the biological destruction is light. The light adjustments vary depending on the type of organisms, lightening quality, quantity and duration. In the dark, it should be considered that some insects and microorganisms (fungus and actinomycete) ceased their developments (Caneva et al. 1991).

Choosing the proper cleaning methods may be useful for the biological control and prevention of the destruction. These are indirect methods. They purify the organic and inorganic materials deposited on the surface of the work of art (actually these materials are often nourishing factors for many organisms) and thus prevent the biological deterioration. The use of some biocides, effective types for microflora on stones such as aqueous TBTO (bis(tri-*N*-butyltin)oxide), CTMQ (cetyltrimethylammonium chloride), copper and silver nitrate and polybor (complex cyclic borates), are suggested by Ginell and Kumar (2004).

Cleaning process prevents deposits in the form of biological diffusion (spores, insect eggs, etc.) which cause infection. Maintaining the control of outside temperature and humidity may be helpful in reducing the biological development. In highly humid environment, a protective cover reduces intense moisture and water absorption. For example, archaeological sites may be retained in the rain. The stone is to be preserved, reduces the permeability and increases the resistance to the water. A complete control of temperature in the outdoor areas is often impossible. Simple shade panels and other shading methods can be used.

Protection of monuments and historic buildings from birds, particularly swallows and pigeons, is another problem. Wires and black nylon nets are the most commonly used methods to avoid them to roost and nest but may result in aesthetic problems if not be given attention to appropriate details. In recent years, new protective gels effective on pigeons have been developed, based on the principle of annoying birds by creating a soft ground. This gel is not sticky and do not stain stone. High-voltage wires are a solution, but there is the short-circuit problem. Avoiding biological growth will help in the protection of archaeological sites and external environment.

In terms of the relationship between environmental factors and plants, planting may be a solution to the problem of stone building protection. For instance, a suitable plantation provides the following effects:

- The water level is reduced by using plants like a biological pump.
- Creating solar panel, microclimate is regulated with plants by minimizing evaporation and radiation.
- Tree planting blocks the wind and wind erosion is reduced.
- Reduce air pollution. Plant selection is important. The roots must not give damage to the buildings.
- In the sun-effective west aspects, plantation is made to form barrier, and so the extreme UV damage to building materials (melting, colour change, etc.) can be kept under control.

10.6 Conclusions

The environment is a broad concept in which all living ecosystems, from microorganisms to plants and animals, interact as a whole. It changes locally or globally as a result of human activities in many directions. These are changes such as temperature, carbon dioxide, rainfall, UV radiation, ozone, acidification and nitrification, and they have direct negative effects on ecosystems and lichen communities. Natural and human-induced adverse factors (such as air pollutants) and various external factors pose a threat to the continuity of the equilibrium. Haemerobic events, such as a rapid climate change, should be taken into account when environmental protection strategies are being developed and protection areas are being selected, so that taxa and ecosystems are being protected.

The long evolutionary history of lichens has seen many catastrophic events in the planet's terrestrial environment, and they will probably succeed in getting rid of it in the future with their unique microbial symbiotic systems.

In addition to a number of significant ecological roles in the environment, biodeteriorative organisms as well as lichens cause weathering of stone substrates. In the case of ancient monuments, biodeterioration of cultural heritage seems a complicated problem, and rational measures should be taken for conservation of these artefacts. For the preservation of historical and artistic stone works, it is necessary to struggle with lichens and similar organisms. The application of preventive approaches to the formation of living organisms is the best way to both avoid harming species and protect these artefacts.

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