6

Lichens: Sensitive Indicators of Improving Air Quality

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Biological monitoring is the application of assessment techniques using plants or other biological material to gain information about the quality and condition of the environment (Cairns 1980). Plants are greatly affected by the physical and chemical environment in which they live. If conditions become altered, the exposed plant community can accurately reflect these changes and can thus be important indicators of the state of the environment (Nash 1988). Plants also collect contaminants from the air and soil and can be sampled from various geographic locations to assess the amount of contaminant present.

This chapter discusses the value of lichens as biomonitors and documents their increased abundance in Sudbury after reductions in sulfur dioxide emissions. This reinvasion by lichens represents some of the best evidence of the natural recovery of the terrestrial ecosystem and thus the importance of the industrial pollution abatement programs that began in the early-1970s.

Lichens

Lichens form conspicuous gray, green, orange, or red patches on trees or rocks (Fig. 6.1). They are composite symbiotic organisms with both an algal and a fungal partner; approximately 90% of the mass is made up of the slow-growing fungal partner. The fungus supplies structural support, and the algal cells support nutrition through photosynthesis.

There is a long history of lichens being used as a sensitive indicator of air quality, particularly with regard to sulfur dioxide in urban areas or near point source emissions (Ferry et al. 1973; Burton 1986; Richardson 1992). Naturalists first observed the disappearance of lichens from polluted areas soon after the start of the Industrial Revolution (Turner and Borrer 1839). In 1859, Grindon observed that "the quality [of lichens near Manchester] has been much lessened . . . through the influx of factory smoke which appears to be singularly prejudicial to these lovers of pure air." As air quality has improved in many industrial centers in western Europe, there has been a marked improvement in lichen abundance (Seaward 1989).

Although lichens are generally very sensitive to air pollutants, not all lichen species are equally affected. At a given sulfur dioxide concentration, certain species disappear while others remain. In Europe, Hawksworth and Rose (1976) developed a scale that relates the occurrence of particular lichens to winter sulfur dioxide levels.

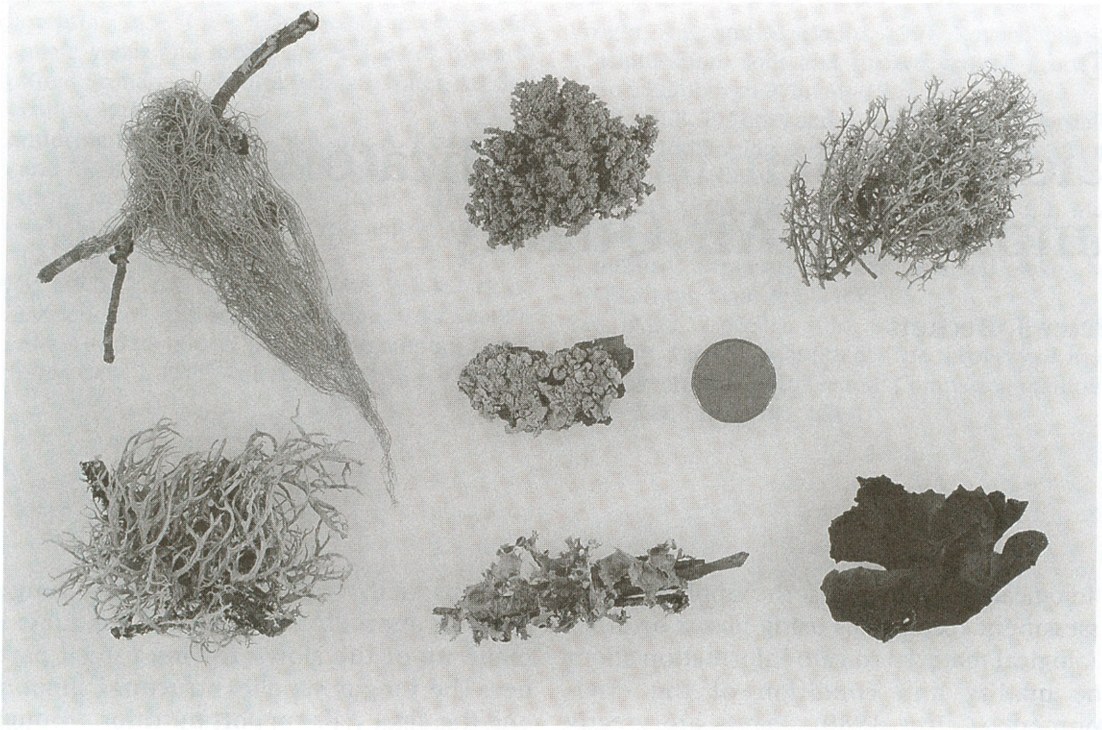


FIGURE 6.1. Examples of typical lichens associated with pollution studies in the Sudbury area. *Top row (L–R)*: *Usnea hirta* (epiphyte), *Stereocaulon* sp. (rock), *Cladina rangiferina* (soil). *Center*: *Parmelia sulcata* (epiphyte). *Bottom row (L–R)*: *Evernia mesomorpha* (epiphyte), *Cetraria ciliaris* (epiphyte), *Umbilicaria mulhenbergia* (rock). The coin provided for scale is a $1 Canadian "Loonie."

Characteristic of Lichens as Sensitive Biomonitors

The suitability of using lichens in biomonitoring studies is summarized in Table 6.1 and briefly discussed in the following section.

Lichen species may be conveniently grouped into three morphological forms that are related to their sensitivity to air pollution. Crustose forms cover and tightly adhere to the substrate; foliose lichens are leaflike with many lobes and loosely adhere to the substrate; fruticose lichens grow vertically upward or hang down from twigs (Fig. 6.1). Because of their elongated growth form, fruticose lichens (see Plate 8 following page 182) are generally more exposed to contaminants than crustose and foliose lichens.

TABLE 6.1. Advantages of using lichens as biomonitors

1.	Accumulate substances in measurable quantities
2.	Available in sufficient quantities over a wide geographic area to ensure unbiased sampling
3.	Present throughout the year with relative ease of collection. May be sampled repeatedly
4.	Have various sensitivities to a contaminant to allow a series of communities to form in response to the concentration of the contaminant

A particularly important morphological characteristic of lichens, with regard to their use as biomonitors, is the absence of an outer protective waxy cuticle; this allows contaminants to move freely into the lichens. Because lichens are adapted to obtaining nutrients from rain, they possess the ability to take up elements both passively and directly from the surrounding environment. The cell walls act like the ion-exchange resins found in water softeners and bind with substances found in rainwater. Also, the open spongelike structure of the fungal partner allows gases such as oxygen, carbon dioxide, and sulfur dioxide to readily diffuse into the body of the lichen. The surface structure of the lichen also traps a variety of airborne particulates that range from harmless dust particles to radionuclides (Box 6.1).

The outstanding ability of lichens to accumulate substances either from the air or other parts of the environment has allowed wider application than indication of air quality (Nieboer and Richardson 1981). For instance, these organisms have been exploited for geobotanical prospecting (Box 6.2).

Box 6.1. Chernobyl Accident and Lichens

Lichens can effectively monitor radioactive isotopes. This was shown on April 26, 1986, when an explosion occurred in the Chernobyl nuclear-powered electricity generating plant in the Ukraine (Smith and Clark 1986). The explosion and subsequent fire released a plume of radioactive particles for several days before controls were implemented. The main plume moved west over Poland and the Alps and reached Britain 1 week later. It then moved north to deposit significant amounts of radioactive material over Scandinavia (Steinnes and Njastad 1993), with subsequent economic consequences for Lapp reindeer herders. High levels of cesium (^{137}Cs) were found in the meat of many reindeer; up to 10,000 Bq cesium per kilogram was documented. The legal limit for sale is 300 Bq/kg. Most of this radionuclide was ingested by reindeer feeding on highly contaminated lichens. In Poland, there was a startling increase of cesium (165-fold) in *Umbilicaria* after the passage of the Chernobyl cloud across the country. In this case, heavy rain washed out some of the radioactive material, which was subsequently taken up by the lichen. The radioactive cloud arrived in Canada 11 days after the accident. Samples of reindeer/caribou lichen, *Cladina rangiferina*, were collected across the Maritime provinces. Using computer simulation models for deposition, investigators estimated that the cloud crossed the Maritimes at a height of 10,000 m (Smith and Ellis 1990). Once again, lichens were shown to be excellent collectors of aerosol-size particles owing to their high surface/mass ratio and slow growth rates.

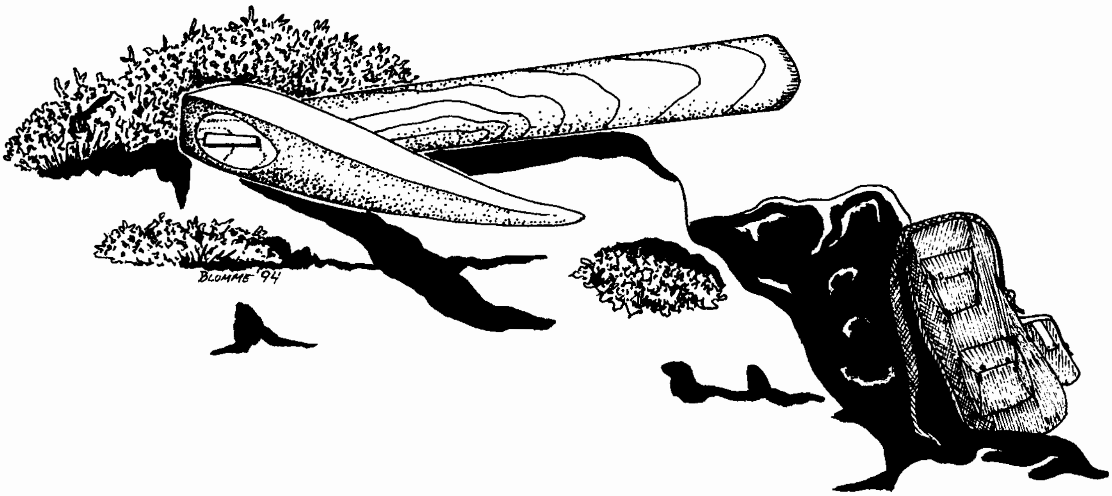
Studies Involving Lichen Biomonitors in the Sudbury Area

Lichen Distribution and Changes over Time

Three surveys have been made of lichens growing on mature balsam poplar (*Populus balsamifera*) tree trunks in the Sudbury area. The first survey was conducted in 1968 (Leblanc et al. 1972) 4 years before the major pollution control initiatives of 1972 (see Chapter 4). The post-emission-reduction surveys were conducted in 1978 (Beckett 1984) and 1989–1990 (Pappin and Beckett in press). Consistent survey techniques were maintained throughout. Ten trees were chosen at each site, and each tree was carefully examined from the base to a height of 2 m. Lichen species present and percentage cover of each species were recorded. Species richness was estimated for each site using the method of Leblanc and De Sloover (1970) to provide an index value for classifying air quality effects on lichen communities. This classification method assigned a score or index of atmospheric purity (IAP) values to lichen communities at each site. The IAP values were then plotted and joined by isometric lines to delineate various zones (1–5) of atmospheric contamination.

The results of the LeBlanc et al. (1972) survey in 1968 (pre-emission reduction) are shown in the upper panel of Figure 6.2. The most heavily affected area, zone 1, covered much of the barren area described in Chapter 2. Zero to four species of lichen were found in this zone, which is commonly referred to as a "lichen desert." In the next zone, zone 2, fewer than 10 species of lichens were observed. This slightly better but still heavily damaged area corresponds generally to the semibarren vegetation

Box 6.2. Geobotanical Prospecting



The recognition that some plants grow on soils rich in metals (metallophytes) has led to the development of the science of geobotany, whereby a prospector searches for particular plants while investigating the geology in the anticipation of finding mineral deposit. Another strategy is to determine the metal content of plants as an indication of nearby mineral deposits. The physical appearance of the plant can also be an important clue. For example, crustose lichens growing near mineralized rocks may develop characteristically colored thalli (Easton in press), whereas the dark green thalli of certain *Lecanora* species is associated with copper-rich rock.

Foliose lichens are often used for geobotanical prospecting because they are easy to sample. Lichen samples taken from serpentine rocks are often found to accumulate nickel. Around Contwoyoto Lake, Northwest Territories, high levels of copper were found in *Cetraria* (Tomassini et al. 1976). Later, a mining company independently found an economic copper deposit in the same area. *Cladina* (reindeer or caribou lichens) removed from a rocky outcrop in the Elliot Lake area of Ontario contained high levels of uranium that had been accumulated from a vein containing high levels of the radioactive metal.

zone described in Chapter 2 and by Amiro and Courtin (1981). Species diversity and numbers of particularly sensitive species increased progressively through zones 3 to 5. Zone 5 showed only minor effects caused by sulfur dioxide emissions from Sudbury and was described by Leblanc et al. (1972) as the undisturbed or background condition.

The survey of 1978, which occurred 6 years after the major emission reductions and plant closures, dramatically demonstrated the biological benefits of improving air quality (middle panel Fig. 6.2). At this time, the lichen desert (zone 1) had shrunk dramatically (20% of 1968 area). There were now 10 species growing in zone 2. Farther away from the working smelters (zone 3), 20 species were found. Still farther away in zone 4, 25–30 species were present, and in the outer area of lowest pollution, more than 35 species were present (Beckett 1984).

By 1990 (lower panel Fig. 6.2), the lichen desert had completely disappeared, and zone 2 was reduced to two small areas around each of

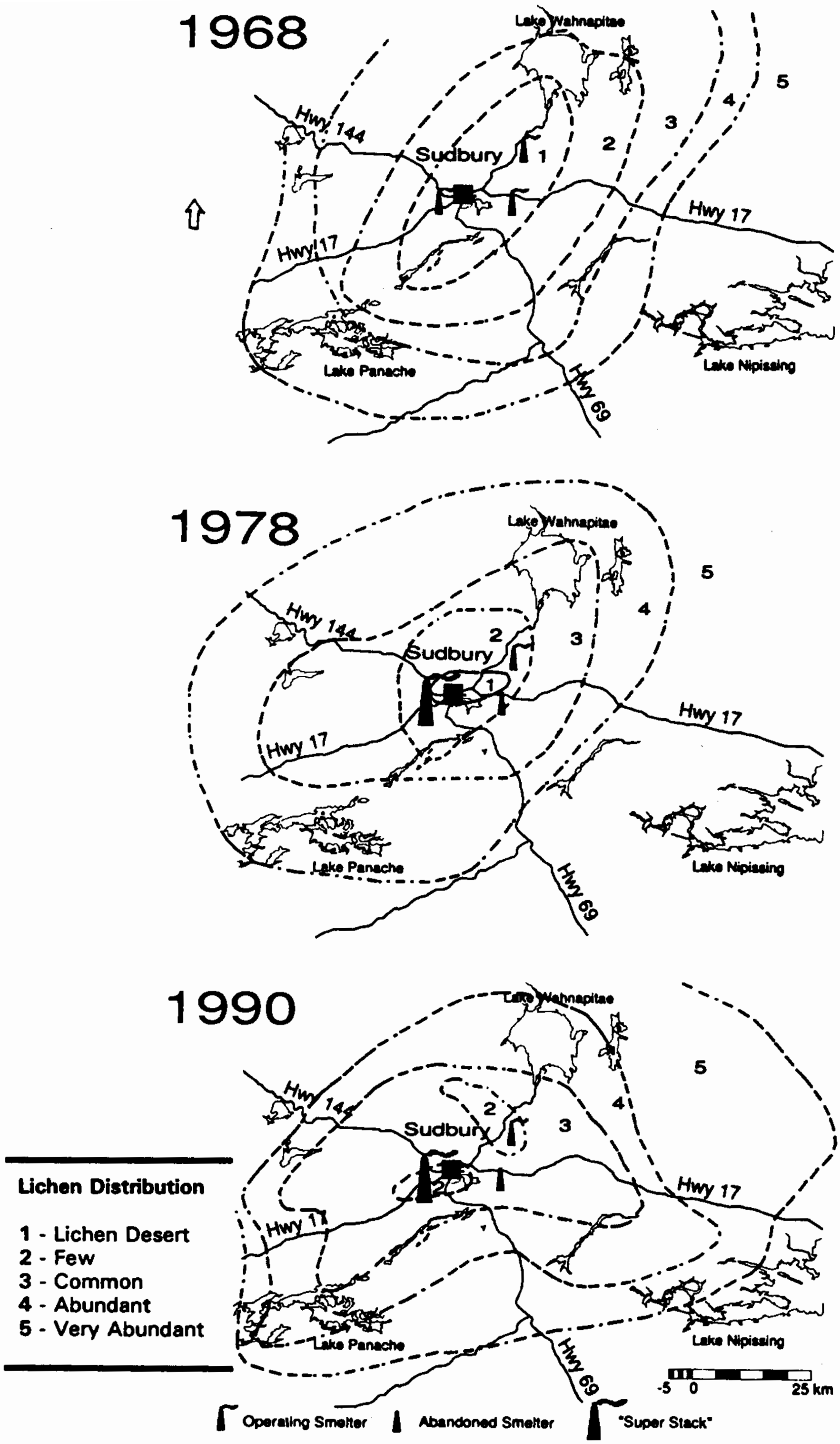


FIGURE 6.2. Zones of atmospheric purity from the 1968, 1978, and 1989–1990 lichen surveys. Note the large zone 1, lichen desert, around the three operating smelters in 1968 (*upper panel*). In 1978, zone 1 has decreased and has been replaced by zone 2 through lichen re-invasion (*middle panel*). In 1989–1990, zone 1 has been eliminated and zone 2 has split into two small zones around the existing two smelters (*lower panel*).

the currently operating smelters. Zone 3 also showed a significant constriction. Overall, the effect was that of a general constriction of the classified zones as more and more lichens colonized the area. Many of the observed lichens in the newly established areas were very small young lichens; further evidence that the colonization was a relatively recent event.

Near Sudbury more than twice the cover was recorded in the 1989–1990 study (Table 6.2) as was observed during the 1968 survey. In 1968, no lichen species occurred within a radius of 7 km from the three smelters (Leblanc et al. 1972). Between 7 and 15 km, only the crustose lichens *Bacidia chlorococca*, *Lepraria aeruginosa* (*incana*), and *Lecanora saligna* and the foliose lichen *Parmelia sulcata* (foliose) were present. By 1990, no sampled trees were found to be devoid of lichen epiphytes, and a majority of the sulfur dioxide-tolerant species (listed above) were found within 2 km (the minimum sampling distance) of the two existing smelters (Pappin and Beckett in press).

Some pollution-sensitive species re-invaded the area much faster than expected, and recolonization did not follow an orderly sequence, with pollution-tolerant species invading ahead of sensitive species (also see Hawksworth and McManus 1989). Results from the 1990 survey indicated that fruticose species, previously reported as rare and sulfur dioxide-sensitive (*Usnea hirta* and *Evernia mesomorpha*), occurred much closer to the smelter (5 km) than expected (Sigal and Johnston 1986).

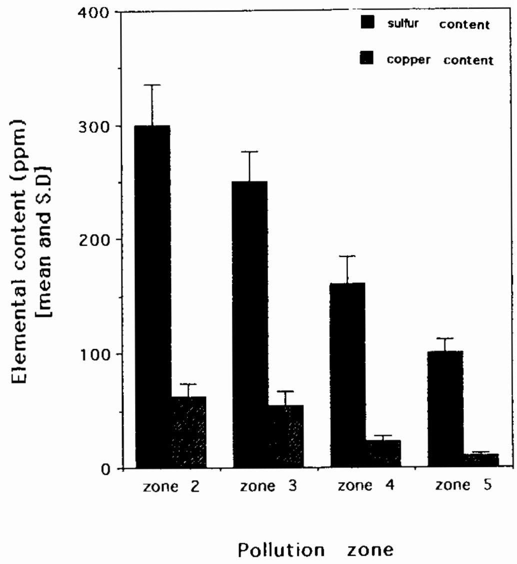
Overall, an increase in the abundance and diversity of lichens in the area closest to the sources of sulfur dioxide has been observed during the past two decades. During this period, annual average concentrations of sulfur dioxide have dropped by two-thirds and short-term fumigations have also declined (see Chapter 4). Recolonization by lichens was rapid (<6 years); confirming studies in England where lichens re-invade an area within 5–10 years after pollution reductions (Seaward 1989). In London, there was a marked increase in lichens through 1970–1988, and recolonization occurred at a faster rate than expected. This was attributed to rapid improvement in London's air quality rather than microclimatic changes (Hawksworth and McManus 1989).

TABLE 6.2. Lichen species observed on balsam poplar in the vicinity of Sudbury, Ontario, Canada, in 1989–1990

Species	Growth form
Biatora (*Lecidea*) *helvola* (Körber ex Hellbom) H. Olivier	Crustose
Buellia stillingiana J. Steiner	Crustose
Caloplaca flavovubescens (Hudson) Laundon	Foliose
Candelaria concolor (Dickson) B. Stein	Foliose
Candelariella vitellina (Hoffm.) Muell. Arg.	Foliose
Cetraria ciliaris Ach. (var. *halei*)	Foliose
C. pinastri (Scop.) S. Gray	Foliose
C. sepincola (Ehrh.) Ach.	Foliose
Cladina rangiferina (L.) Nyl.	Fruticose
Cladonia botrytes (K. Hagen) Willd.	Fruticose
C. coniocraea (Flk.) Spreng.	Fruticose
C. cristatella Tuck.	Fruticose
C. fimbriata (L.) Fr.	Fruticose
C. rei Schaer.	Fruticose
Evernia mesomorpha Nyl.	Fruticose
Hypogymnia physodes (L.) Nyl.	Foliose
Lecanora pulicaris (Pers.) Ach.	Crustose
Lecanora symmictera Nyl.	Crustose
Lepraria incana (L.) Ach.	Crustose
Melanelia subaurifera (Nyl.) Essl.	Foliose
Parmelia exasperatula Nyl.	Foliose
P. sulcata Taylor	Foliose
Parmelina aurulenta (Tuck.) Hale	Foliose
Pertusaria ophthalmiza (Nyl.) Nyl.	Crustose
Phaeophyscia adiastola (Essl.) Essl.	Foliose
P. pusilloides (Zahlbr.) Essl.	Foliose
P. rubropulchra (Degel.) Essl.	Foliose
Physcia adscendens (Fr. H. Olivier)	Foliose
P. aipolia (Ehrh. ex Humb.) Furnr.	Foliose
Physconia detersa (Nyl.) Poelt	Foliose
Rinodina dakotensis Magn.	Foliose
Scoliciosporum bacidia chlorococcum (Graewe ex Stenh.) Vezda	Crustose
Usnea hirta (L.) Weber ex Wigg.	Fruticose
Xanthoria fallax (Hepp in Arn.) Arn.	Foliose

In the 1968 study (Leblanc et al. 1972), the drastic reduction in epiphytic lichens was observed where the mean level of sulfur dioxide was more than 0.02 ppm, with slight reductions where the sulfur dioxide levels were about 0.01 ppm. The improvement from 1978 to 1990 coincides with sulfur dioxide levels across the whole area, dropping to about 0.01 ppm on an annual basis (see Chapter 5). How-

FIGURE 6.3. Sulfur and copper content plus standard deviation of *Parmelia sulcata* collected from 10 trees in each of the 1990 pollution zones.



ever, substrate pH can also influence the richness of the lichen community. Bark with more alkaline pH is better able to buffer the acidity and supply calcium ions to the lichens. The acidity of balsam poplar bark has only decreased slightly from 1978 to 1990 (pH 3–4) and is still considered inhibitory to lichen growth.

Although improvements are apparent in sites close to the smelters, there is evidence that at sites in zone 5, there is a reduction in total lichen diversity. This may be due to changes in the habitat, including age of trees, shading, or effects of long-range transport of contaminants from locations other than Sudbury. No simple causal relationships for the observed changes in lichen communities can be established, but there are strong correlations between the described IAP zones and air quality parameters related to smelter emissions. For example, there is a direct relationship between sulfur or copper content of lichens and the pollution zone from which the lichens were sampled (Fig. 6.3).

There are few epiphytic lichen studies around nickel smelters with which to compare Sudbury. In Russia, around the Severonickel smelter, there is an epiphytic lichen desert (no lichens) within 4 km of the works. Between 8–12 km only 4 species are found. Closer than 12 km is considered as complete destruction of the epiphytic lichens by Gorshkov (1993a) and corresponds to IAP zone 1 in Sudbury. Between 12 and 60 km an increasing diversity of lichens is found, corresponding to IAP zones 2–4. Typical species richness (over 70 species) occurs at distances greater than 60 km (equivalent to IAP zone 5). This pattern corresponds to the Sudbury pattern when emissions were at a maximum in the 1960s.

Comparison to Lichens Growing on Soil or Rock

Although epiphytic lichens suspended in the air have shown a recovery in the past 20 years, lichens on rocky outcrops (saxicolous) and on soil (terricolous) have been much slower to respond (Fig. 6.4). In 1945, Cain reported that only crustose lichens and *Stereocaulon* were found in the most highly polluted zone (approximately 20 km around the smelters). Permanent plots (established in 1977) throughout the inner Sudbury area have demonstrated the slow colonization of rocks by tolerant crustose species of *Lecidea, Lecanora, Porpidia,* and *Rhizocarpon* and by the nitrogen-fixing *Stereocaulon* (fruticose). Other fruticose species

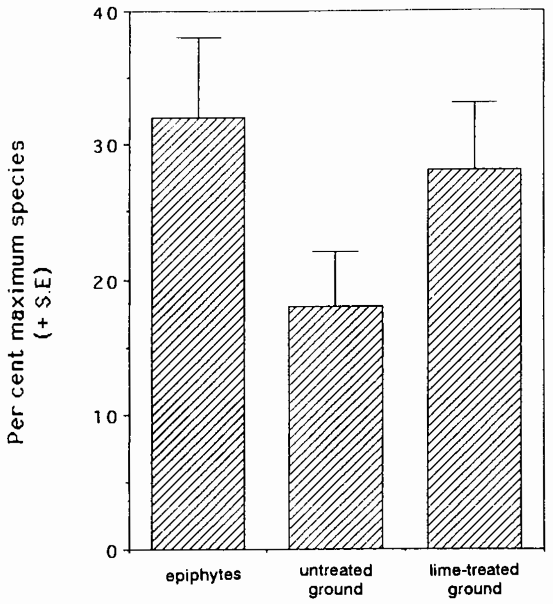


FIGURE 6.4. Comparison of re-invasion rates of lichens for 15 tree plots and nearby ground plots within 25 km of the Copper Cliff smelter between 1978 and 1993. Results are expressed as percentage of the maximum number of expected species for each community type.

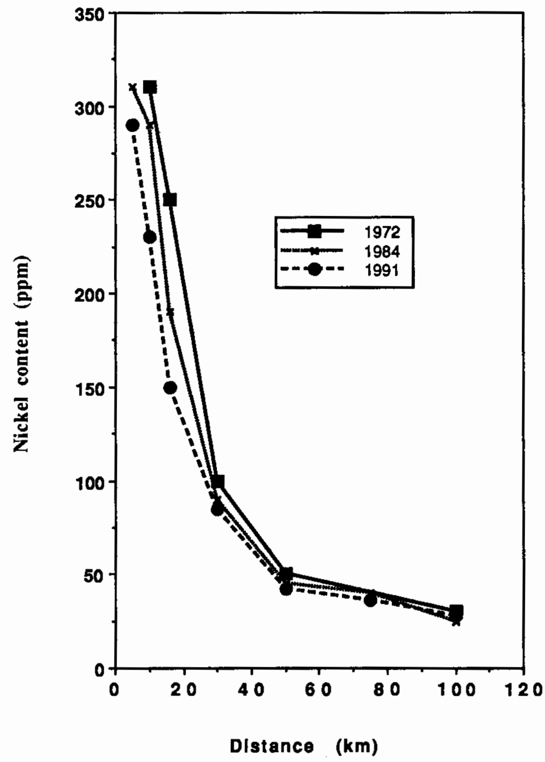
such as *Cladonia rei, C. pleurota, C. deformis,* and *C. cristatella* have invaded soil, especially where some moss (*Pohlia nutans*) is present. Reindeer or caribou lichens (*Cladina rangiferina* and *C. mitis*) occur 20–25 km from the smelters (Cox 1993) with little change in distribution since 1977. This sequence is similar to the distribution that was observed by Folkeson (1984) around a brass foundry in Sweden. In the Kola peninsula (Russia), no soil or rock lichens occur within 3 km of the Severonickel smelter complex (Gorshkov 1993a). *Cladonia* are abundant beyond 8 km and *Cladina* is found at 12 km (Gorshkov 1993b), a situation similar to Sudbury.

The iron-rich black encrustation on the rock, a characteristic of sites within 25 km of the Sudbury smelters, may inhibit lichen colonization. Continuing high soil acidity and metal contamination (see Chapter 4) may contribute to much slower ground recolonization rates as compared with recolonization by epiphytes. Despite having similar acidity, metals, in particular aluminum, are less available in bark to inhibit colonization. On soils treated with limestone, where metals are less available, many more lichens are found compared with untreated soil (Fig. 6.4).

Metal Particulates in Lichens

Lichens are able to accumulate metals by trapping particulates (normally sulfates, sulfides, and oxides). Also, dissolved metal ions bind to exchange sites on cell walls, and there is a slow uptake of metals into the algal cells and fungal hyphae (Richardson et al. 1980). Less than 50% of the total metal content is located within the cell or hypha (Brown 1985). From industrial processes, metal-rich emissions are typically in the form of insoluble particulates. The small particulates become entrapped between the hyphae and often build up in the central (medulla) region of the thallus. The linear correlation between metal content of lichens and that found in collected particulates of filters (Saeki et al. 1977) is used as evidence of particulate accumulation in lichens. Further evidence of particulate trapping is the comparison of iron/titanium ratios. In lichens, these ratios are generally of the same magnitude as those found in regional rocks or in industrial areas as detected in industrial emissions (Richardson and Nieboer 1981;

FIGURE 6.5. Changes in nickel concentration in the foliose lichen *Stereocaulon* collected along a transect northwest of the Copper Cliff smelter in 1972, 1984, and 1991 (1972 data from Tomassini et al. 1976).



Nieboer et al. 1982). Scanning electron microscopy has facilitated examination of particulates trapped in thalli.

Figure 6.5 shows the typical trend for nickel content of *Stereocaulon*, a fruticose lichen common on rock outcrops, at various distances northwest of the Copper Cliff smelter. Close to Copper Cliff, the nickel content is high (approximately 300 ppm) but then drops rapidly with distance, reaching background levels of a few parts per million (Richardson et al. 1980; McIlveen and Negusanti 1994) beyond 100 km. In addition to distance from sources, prevailing wind direction and topography may also affect the pattern of fallout. Prevailing winds in the area are from the north in the winter and southwest in the summer months (Chapter 1).

Over the past 20 years, there has been a small but steady decline in the metal content of the lichens (Fig. 6.5). The observed change (by 25–30% near the smelter and by 10% at distant localities) is less than might be expected given the reduction in metal emissions from the smelters. Suspended particulates in air and associated nickel content is estimated to have decreased by 50% (see Chapter 5). This discrepancy may be partly explained by previously emitted particles containing metals being redistributed as wind-blown dust rather than just reflecting the actual long-term changes in deposition of metals. Studies by Walthier et al. (1990) demonstrated that residence time for metals in lichens is between 2 and 4 years. Thus, lichens can be expected to show significant changes in elemental content 2–3 years after a reduction in metal emissions.

Summary

The improvement in lichen abundance is attributable to the atmospheric cleanup, particularly the reductions in sulfur dioxide emissions that have occurred since 1972. The changes in lichen abundance clearly demonstrate that terrestrial systems show resiliency and can exhibit positive responses to emission controls.

This study shows that the distribution of sensitive lichen species and the overall lichen community structure were useful measures to delineate areas of poor air quality and to monitor improvement after reductions in atmospheric emissions. Lichens were the first biota to respond to changes (before aquatic communities, Chapter 5) and, as such, provide an important sensitive measure or "barometer" of the health of the industrial ecosystem.

Additional legislation further tightening emission controls became effective in 1994. These new measures should cause a further improvement of the Sudbury area ecosystem as a whole and further constrict the damaged lichen zones around Sudbury. If current trends continue, perhaps by the year 2000, there will be at least 10 lichen species on trees around the smelters. Also, as soil conditions improve, there should be a gradual invasion by ground-dwelling lichens, provided that lichens can compete with mosses and vascular plants for space. Wherever there are significant reductions in sulfur dioxide emissions and, to a lesser extent, metals, there should be a recovery in the lichen flora. This process appears to be rapid provided there are sources of colonizing lichens within a reasonable distance from the damaged area. Not only would this recovery be expected around smelters but also around other similarly affected areas when clean air programs are put into operation.

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