ISSN 1067-4136, Russian Journal of Ecology, 2017, Vol. 48, No. 4, pp. 335–339.

Initial Stages of Recovery of Epiphytic Lichen Communities after Reduction of Emissions from a Copper Smelter

I. N. Mikhailova

Institute of Plant and Animal Ecology, Ural Branch, Russian Academy of Sciences, Yekaterinburg, 620144 Russia
e-mail: mikhailova@ipae.uran.ru

Received May 12, 2016

Abstract—Analysis has been made of changes in the species composition and abundance of epiphytic lichens on fir trees during the first decade after a sharp reduction of emissions from a large copper smelter in the Middle Urals. The results show that lichens have recolonized the area of the former lichen desert and that the abundance of lichen species in the impact and buffer zones has increased. However, a fairly long time is required before lichen communities in the vicinity of the smelter can recover to the background state, since species highly sensitive to pollution still occur only in the background area.

Keywords: recolonization, succession, resistance, elasticity, heavy metals, sulfur dioxide, industrial pollution, the Middle Urals

DOI: 10.1134/S1067413617030110

Reduction of industrial emissions in the past few decades has provided a unique possibility to study the initial stages of recovery of natural ecosystems damaged by the long-term impact of toxic pollutants. Epiphytic lichens are one of the most vulnerable components of terrestrial biota that sensitively responds both to direct toxic impact and to its consequences for ecosystems, particularly fragmentation of habitats and changes in their microclimate due to degradation of tree stand and ground vegetation layer [1]. Taking into account certain biological features of lichens, such as slow rates of growth and development and low efficiency of colonization of new substrates, it is unlikely that their community will recover within a short time after the removal of toxic load. Moreover, no pool of lichen vegetative diaspores exists in polluted areas: it has been shown that nondeveloping soredia die and disappear from the substrate within a few months [2].

Most studies on the recovery of lichen communities have been performed in urban environments [3–8, etc.], where it is fairly difficult to identify the leading factor determining the dynamics of lichen communities. Areas around point polluters are more promising in this respect, but studies on the recovery of lichens in regions exposed to the impact of large industrial emission sources are very few [9, 10]. To gain an insight into the pattern of recovery of lichen communities, it is necessary to further accumulate relevant information on different natural zones and types of industries.

The purpose of this study was to analyze the dynamics of species composition and frequency of epiphytic lichens on trunks of Siberian fir trees (*Abies sibirica* Ledeb.) during the first decade after a sharp reduction of emissions from a large copper smelter in the Middle Urals. The test hypothesis was that this period should give rise to recolonization of "lichen desert" by species with a high colonization potential but tolerant of residual pollution.

MATERIAL AND METHODS

The Middle Urals Copper Smelter (MUCS) is located in the suburbs of Revda, Sverdlovsk oblast. The main toxic components of emissions from this source are sulfur dioxide and heavy metals. The amount of emissions reached 140000 t per year in the late 1980s but was then reduced to 71000–96000 t in 1995–1998, 24000–34000 t in 2003–2008, and 3000–5000 t in 2010–2013 [11]. Studies performed in 1990 to 1997 revealed distinct concentric zones with different degrees of damage to forest ecosystems around the MUCS [12], including damage to epiphytic lichen communities [13–15]. Analysis of the dynamics of forest vegetation during the first decade after the reduction of emissions has shown that it is still heavily suppressed in the immediate vicinity of the MUCS: trees continue to die off, and the ground vegetation layer does not recover [11]. Data on the distribution of moles (sensitive indicators of pollution) in this region are also indicative of an adverse environment [16]. This is largely explained by the persistence of high concentrations of heavy metals in the upper soil horizons [17].

The data used as a starting point for this study were collected in 1990 to 1992 in the course of analysis of

Table 1. Dynamics of species composition of epiphytic lichens on fir trunks

Species	Distance from MUCS (km), period							
	1–2		4		7		30	
	I	II	I	II	I	II	I	II
Bryoria nadvornikiana (Gyelnik) Brodo & D. Hawksw.	–	–	–	–	–	–	+	+
Chaenotheca ferruginea (Turner ex Sm.) Mig.	–	–	+	+	+	+	+	+
Cladonia coniocraea (Flörke) Spreng.	–	+	+	+	+	+	+	+
C. fimbriata (L.) Fr.	–	–	–	+	–	–	+	+
Evernia mesomorpha. Nyl.	–	–	–	–	–	–	+	+
Fuscidea arboricola Coppins & Tonsberg.	–	–	–	–	–	–	+	+
F. pusilla Tønsberg	–	–	–	–	–	–	+	+
Hypocenomyce caradocensis (Leight. ex Nyl.) P. James & Gotth. Schneid.	–	+	+	+	+	+	+	+
H. scalaris (Ach. ex Lilj.) M. Choisy.	–	–	–	–	–	–	+	+
Hypogymnia physodes (L.) Nyl.	–	+	+	+	+	+	+	+
Lecidea nylanderi (Anzi) Th. Fr.	–	–	–	–	–	–	+	+
Lecanora sp.	–	–	–	–	+	–	+	+
Lepraria elobata Tønsberg	–	–	–	–	–	+	+	+
Micarea denigrata (Fr.) Hedl.	–	–	–	+	–	+	+	+
Parmelia sulcata Taylor	–	–	–	–	–	–	+	+
Parmeliopsis ambigua (Wulfen) Nyl.	–	–	–	–	–	–	+	+
Placynthiella uliginosa (Schrader) Coppins & P. James	+	+	–	+	–	–	–	–
Scoliciosporum chlorococcum (Graewe ex Stenh.) Vězda	+	+	+	+	+	+	+	+
Tuckermannopsis sepincola (Ehrh.) Hale		+	–	–	–	–	–	–
Usnea subfloridana Stirton	–	–	–	–	–	–	+	+
Vulpicida pinastri (Scop.) J.-E. Mattsson & M.J. Lai	–	+	+	+	+	+	+	+
Number of species	**2**	**7**	**6**	**9**	**7**	**8**	**19**	**19**

Periods: (I) 1990–1992, (II) 2014–2015. Plus and minus signs indicate the presence or absence of a particular species (here and in Table 2).

epiphytic lichen successions on the trunks of fir trees in three zones with different pollution levels [14]: impact (4 km west of the MUCS), buffer (7 km), and background (30 km). A total of 190 trees over 40 years of age were included in analysis. The area within a radius of 1–2 km from the MUCS was surveyed by the route method during the same period.

In 2014 and 2015, we surveyed permanent test plots located at distances of 1–2 km from the MUCS (seven plots) and at 4, 7, and 30 km from it (five plots each). To estimate the abundance of lichens, five fir trees were examined in each plot. In addition, 50 more trees were examined to reveal lichen flora at each of the above distances. All species found on the trunks at a height of up 2 m were recorded. The abundance of macrospecies was evaluated in terms of frequency, i.e., the proportion of colonized trees. The significance of differences in frequency during different periods was estimated by Fisher's exact test. Similarity in species composition was evaluated using the PAST 3.12 software package.

RESULTS AND DISCUSSION

A total of 21 lichen species were found on fir trunks over the study period (Table 1). In 1990–1992, the area in the immediate vicinity of the MUCS was a "lichen desert" where only highly tolerant *Scoliciosporum chlorococcum* and epixylic *Placynthiella uliginosa* were recorded, with the latter sporadically spreading from decaying wood to bare soil surface and tree bases.

By 2014, this zone was colonized by pollution-tolerant *Cladonia coniocraea* and *Hypocenomyce caradocensis* and also by medium-sensitive *Hypogymnia physodes* and, to a lesser extent, *Vulpicida pinastri*. All these species were previously recorded in the impact zone (4 km from the MUCS), from where they have probably spread after the removal of toxic load. In addition, *C. coniocraea* can spread to the trunks from other substrates within the former lichen desert, since it sporadically occurs on decaying wood in polluted areas.

Experiments on cultivation of soredia showed that the thalli of *H. physodes* in the study region grow

Table 2. Dynamics of the frequency of macrolichens on fir trunks (proportion of colonized trees, %)

Species	Distance from MUCS (km), period							
	1–2		4		7		30	
	I	II	I	II	I	II	I	II
Cladonia coniocraea	–	68.6	64.4	96.0*	67.9	100.0*	100.0	100.0
C. fimbriata	–	–	1.4	–	–	–	3.2	4.0
Evernia mesomorpha	–	–	–	–	–	–	9.4	4.0
Hypogymnia physodes	–	45.0	13.7	48.0*	22.6	52.0*	100.0	100.0
Parmeliopsis ambigua	–	–	–	–	–	–	–	8.0
Tuckermannopsis sepincola	–	2.9	–	–	–	–	–	–
Usnea subfloridana	–	–	–	–	–	–	1.6	–
Vulpicida pinastri	–	8.6	1.4	8.0*	1.9	–	32.8	8.0*
Number of trees	**30**	**35**	**73**	**25**	**53**	**25**	**64**	**25**

* Differences between observation periods are significant at $p < 0.05$ (Fisher's exact test).

extremely slowly: the size of thalli at 29 months after inoculation did not exceed 0.5 mm [2]. This fact suggests that recolonization of the area near the MUCs began within a short time after the reduction of emissions, since the size of *H. physodes* and *V. pinastri* thalli found in 2014 reached 4–5 mm.

The set of the above pioneering species of demutational succession generally corresponds to the initial stages of succession on fir stems described in 1990–1992 for the impact and buffer areas [14]. A distinctive feature of demutational succession, compared to natural succession, is that there is no definite sequence in the colonization of trees by these species. Natural successions strictly follow the scheme *C. coniocraea* → *H. caradocensis* → *H. physodes*, because they are conditioned by age-related changes in trees, particularly debranching of the lower part of the trunk and structural modification of the bark [14]. In contrast, any of these lichens may be a pioneer species in demutational succession occurring simultaneously on trunks of different ages; i.e., some trunks may be colonized by *H. physodes* or *H. caradocensis* alone. Typical climax communities of nonpolluted fir–spruce forests characterized by the presence and high abundance of Caliciales lichens (mainly *Chaenotheca ferruginea*) [14] were occasionally found in 2014 and 2015 at a distance of 4–7 km from the MUCS but not in the former lichen desert.

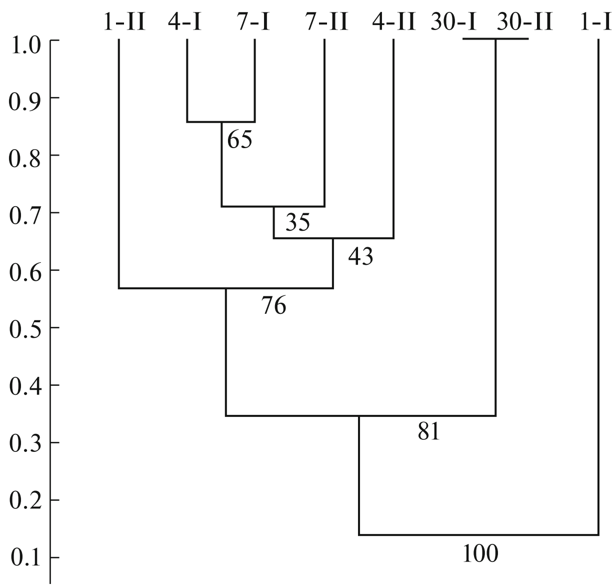
A noteworthy fact is that *Tuckermannopsis sepincola* was found in 2014 on a fir tree in the former lichen desert. This lichen in the study region is a pioneering species on birch trunks and only sporadically occurs on the branches (but not trunks) of fir trees in thinned-out stands. Its frequency in the period of heavy emissions from the MUCS was the highest in polluted areas, which was explained by alleviation of intraspecific competition in epiphytic lichen communities [18]. The appearance of *T. sepincola* on fir trunks confirms that the microclimate of fir–spruce forests near the MUCS has changed: a decrease in air humidity combined with better insolation due to suppression of the tree stand and ground vegetation layer conform to ecological preferences of this species.

The species composition of lichens at 4 and 7 km from the MUCS did not change significantly between the two observation periods, but a significant increase in frequency was noted for the majority of macrolichens (Table.2). The low frequency of *V. pinastri* in the background area in 2014–2015 is probably explained by habitat patchiness reflected in the pattern of species distribution.

Species highly sensitive to pollution (*Bryoria nadvornikiana*, *Evernia mesomorpha, Usnea subfloridana)* still occur only in the background area. This may be due to an insufficient distance of diaspore dispersal, residual pollution load exceeding tolerance thresholds of adult thalli and/or their early developmental stages, or ecotopic conditions unfavorable for the species, mainly low air humidity.

The processes described above are reflected in the increase of species richness in polluted areas (Table 1) and in the clustering of test plots with respect to similarity in the species composition of lichens (figure): the former lichen desert has approached the impact–buffer cluster after the removal of pollution load, whereas previously it was completely isolated from it.

The recovery rates of the lichen communities are generally similar to those in the vicinity of copper–nickel smelter in Sudbury, Canada, where the recolonization of lichen desert started 6 years after reduction of emissions [9]. The desert disappeared by the end of the second decade, but the abundance of lichens increased with the distance from the polluter [9]. The recovery of epiphytic communities completed only 40 years after decommissioning of the smelter [10]. There was no strict relationship between the sensitivity of species and the rate of their recovery: some sensitive



UPGMA dendrogram of similarity in species composition (Jaccard index) between lichen communities growing at different distances from the MUCS (1, 4, 7, and 30 km) and analyzed in different periods (I, 1990–1992; II, 2014–2015). Numbers below branches show bootstrap support (%) from 1000 replicates.

species such as *Usnea hirta* and *E. mesomorpha* proved to colonize this area earlier than it could be expected [9]. In our case, the former desert was colonized not only by pollution-tolerant species but also by medium-sensitive *H. physodes.* Its high colonizing potential was also noted in studies on postpyrogenic successions [19]. Since colonization success largely depends on the numbers of propagules in the environment [20], disturbed territories are colonized primarily by lichen species that are most widespread in the surrounding biotopes.

CONCLUSIONS

The results presented above confirm the initial hypothesis: the recovery of epiphytic lichen communities around a large copper smelter started within the first decade after the reduction of emissions. The area of the former lichen desert is being colonized by highly and moderately tolerant species, and the abundance of lichen species in the impact and buffer areas is increasing. Obviously, a fairly long time is required before lichen communities in the vicinity of the smelter can recover to the background state, provided that not only pollution is completely prevented but also the microclimate typical of undisturbed forests is restored.

ACKNOWLEDGMENTS

The author is grateful to E.L. Vorobeichik and J. Motiejūnaitė for their valuable advice and comments on the manuscript.

This study was supported by the Russian Foundation for Basic Research, project no. 15-04-06828.

REFERENCES

1. *Monitoring with Lichens – Monitoring Lichens,* Nimis P.L., Scheidegger, C., and Wolseley, P.A., Eds., Dordrecht: Kluwer, 2002.
2. Mikhailova, I. and Scheidegger, C., Early development of *Hypogymnia physodes* (L.) Nyl. in response to emissions from a copper smelter, *Lichenologist,* 2001, vol. 33, pp. 527–538.
3. Rose, C.I. and Hawksworth, D.L., Lichen recolonization in London's cleaner air, *Nature,* 1981, vol. 289, pp. 289–292.
4. Kandler, O., Lichen and conifer recolonization in Munich's cleaner air, in *Air Pollution and Ecosystems,* Mathy, P, Ed., Dordrecht: D. Reidel, 1987, pp. 784–790.
5. Hawksworth, D.L. and McManus, P.M., Lichen recolonization in London under conditions of rapidly falling sulphur dioxide levels, and the concept of zone skipping, *Bot. J. Linn. Soc.,* 1989, vol. 100, pp. 99–109.
6. Seaward, M.R.D. and Letrouit-Galinou, M.A., Lichen recolonization of trees in the Jardin du Luxembourg, Paris, *The Lichenologist,* 1991, vol. 23, no. 2, pp. 181–186.
7. Gilbert, O.L., Lichen reinvasion with declining air pollution, in *Bryophytes and Lichens in a Changing Environment,* Bates, J.W. and Farmer, A.M, Eds., Oxford: Clarendon, 1992, pp. 159–177.
8. Bates, J.W., Bell, J.N.B., and Massara, A.C., Loss of *Lecanora conizaeoides* and other fluctuations of epiphytes on oak in S.E. England over 21 years with declining SO_2 concentrations, *Atmosph. Environ.,* 2001, vol. 35, pp. 2557–2568.
9. Gunn, J.M., Lichens: Sensitive indicators of improving air quality, in *Restoration and Recovery of an Industrial Region,* New York: Springer, 1995, pp. 81–92.
10. Schram, L.J., Wagner, C., McMullin, R.T., and Anand, M., Lichen communities along a pollution gradient 40 years after decommissioning of a Cu–Ni smelter, *Environ. Sci. Pollut. Res.,* 2015, vol. 22, no. 12, pp. 9323–9331.
11. Vorobeichik, E.L., Trubina, M.R., Khantemirova, E.V., and Bergman, I.E., Long-term dynamic of forest vegetation after reduction of copper smelter emissions, *Russ. J. Ecol.,* 2014, vol. 45, no. 6, pp. 498–507.
12. Vorobeichik, E.L., Sadykov, O.F., and Farafontov, M.G., *Ekologicheskoe normirovanie tekhnogennykh zagryaznenii ekosistem (lokal'nyi uroven')* (Ecological Rating of Technogenic Pollutants in Ecosystems: Local Level), Yekaterinburg: Nauka, 1994.
13. Mikhailova, I.N. and Vorobeichik, E.L., Epiphytic lichenosynusia under conditions of chemical pollution: Dose–effect dependencies, *Russ. J. Ecol.,* 1995, vol. 26, no. 6, pp. 425–431.
14. Mikhailova, I.N., Epiphytic lichen synusiae in forests of the Middle Urals under conditions of technogenic air pollution, *Extended Abstract of Cand. Sci. (Biol.) Dissertation,* Yekaterinburg, 1996.

15. Scheidegger, C. and Mikhailova, I., Umweltforschung—Flechten als Bioindikatoren für die Luftverschmutzung im Ural: Eindrücke von einem gemeinsamen Forschungsprojekt, in *Naturwerte in Ost und West. Forschen für eine nachhaltige Entwicklung vom Alpenbogen bis zum Ural,* Landolt, R., Ed., Birmensdorf: Eidgenossische Forschungsanstalt WSL, 2000, pp. 55–59.

16. Vorobeichik, E.L. and Nesterkova, D.V., Technogenic boundary of the mole distribution in the region of copper smelter impacts: Shift after reduction of emissions, *Russ. J. Ecol.,* 2015, vol. 46, no. 4, pp. 377–380.

17. Vorobeichik, E.L. and Kaigorodova, S.Yu., Long-term dynamics of heavy metal contents in upper soil horizons in the zone of impact from a copper smelter in the period of reduction in its emissions, *Euras. Soil Sci.,* 2017, vol. 50 (in press).

18. Mikhailova, I., Populations of epiphytic lichens under stress conditions: Survival strategies, *Lichenologist,* 2007, vol. 39, no. 1, pp. 83–89.

19. Kutorga, E., Adamonyte, G., Iršėnaitė, R., et al., Wild fire and post-fire management effects on early fungal succession in *Pinus mugo* plantations, located in Curonian Spit (Lithuania), *Geoderma,* 2012, vol. 191, pp. 70–79.

20. Eversman, S. and Horton, D., Recolonization of burned substrates by lichens and mosses in Yellowstone National Park, *Northwest Sci.,* 2004, vol. 78, pp. 85–92.

Translated by N. Gorgolyuk