Rev Environ Sci Biotechnol (2007) 6:231–259
DOI 10.1007/s11157-006-9117-9

REVIEW PAPER

Industrial barrens: extreme habitats created by non-ferrous metallurgy

M. V. Kozlov · E. L. Zvereva

Received: 6 March 2006 / Accepted: 22 November 2006 / Published online: 21 December 2006

Abstract Industrial barrens are bleak open landscapes evolved due to deposition of airborne pollutants, with only small patches of vegetation surrounded by bare land. These extreme environments appeared as a by-product of human activities about a century ago. The comparative analysis of information available from 36 industrial barrens worldwide allowed to identify factors and conditions that are necessary and sufficient for the appearance of these specific habitats. Vast majority of industrial barrens is associated with non-ferrous smelters, located predominantly in mountainous or hilly landscapes. Development of industrial barrens starts from gradual decline of vegetation due to severe pollution impact accompanied by other human-induced disturbances (primarily clearcutting) and is usually concluded by a fire, facilitated by accumulation of woody debris. Since vegetation recovery is hampered by soil toxicity caused by extreme contamination by heavy metals, soils remain bare and suffer from erosion enhanced by altered microclimate. In spite of general reduction in biodiversity, industrial barrens still support a variety of life, including regionally rare and endangered species, as well as populations that evolved specific adaptations to the harsh and toxic environment. Recently, most industrial barrens show some signs of natural recovery due to emission decline or closure of responsible polluters; some of barren sites have been or are being successfully revegetated. The remaining industrial barrens offer unique opportunities for conducting 'basic' ecological research, in particular for testing some general theories in an evolutionary novel stressful environment; some of barren habitats deserve conservation for scientific and educational purposes.

Keywords Biodiversity · Clearcutting · Conservation · Contamination · Disturbance · Fire · Heavy metals · Microclimate · Pollution · Recovery · Soil erosion

1 Introduction

Naturalists have always been intrigued by the ability of life to sustain conditions inhospitable to humans. Both scientific and popular literature contains numerous descriptions of biota living 'on the edge'—in deserts, on barren soil of polar islands, under Antarctic ice, in deep waters, and in many other more or less unusual conditions. However, all these habitats exist for millennia, and living beings had sufficient time to evolve

---

M. V. Kozlov (✉) · E. L. Zvereva
Section of Ecology, Department of Biology,
University of Turku, 20014 Turku, Finland
e-mail: mikoz@utu.fi

biochemical, morphological and behavioural adaptations allowing to live and even flourish in these ‘extreme environments’. More astonishing is the diversity of life persisting in industrial barrens—extreme habitats that appeared as a by-product of human activities only about a century ago.

The creation of metal-contaminated, phytotoxic land by atmospheric smelter effluents[1] has occurred in many parts of the world (Vangronsveld et al. 1995; Winterhalder 2000) and attracted agitated public attention: “Bushes shrank and vanished. Grasses died away. Blighted land replaced the forest. All around us dead hills, red, raw, ribbed by erosion, stood stark in the sunshine. Hardly two miles from dense woodland we were in the midst of a moonscape on earth. ... We were in the southeast corner of Tennessee, in the Ducktown Desert of the Copper Basin” (Teale 1951).

Unfortunately, industrial barrens are studied much less than other ‘extreme habitats’: the scientists were only called to evaluate the damage (e.g. Haywood 1910; Euler 1939; Dean and Swain 1944) or develop rehabilitation measures (e.g. Carter et al. 1977; Pommerening 1977; Winterhalder 2000). Importantly, information on several industrial barrens is reported only in publications describing reclamation measures (e.g. Pancholy et al. 1975; Sopper 1989; Vangronsveld et al. 1995, 1996; Kelley and Tate 1998; Winterhalder 2000). Even the researchers exploring pollution effects on plant communities tend to select the most polluted sites outside industrial barrens, because these habitats seem not comparable with less disturbed sites (e.g. Banásová et al. 1987). Therefore the first goal of our review is to introduce industrial barrens to a wide range of scientists, showing that these easy-to-reach habitats offer an excellent opportunity for a variety of ‘basic’ ecological and evolutionary studies. From a scientific perspective, unusual anthropogenic ecosystems of denuded barrenland with lifeless lakes can be considered opportunistic macrocosms (unique laboratories) for integrated research on the effects of harsh environmental conditions on ecosystem structure and functions (Nriagu et al. 1998).

Not every strong polluter is surrounded by industrial barrens. Their development seems only possible under specific combination of landscape characteristics, human activities, and co-occurring stressors; however, to our knowledge, no attempt was made to explore this problem by means of comparative analysis. The second goal of our review is therefore to find out both similarities and dissimilarities among the industrial barrens that exist (or did exist) across the Globe and on this basis identify the factors and conditions that are necessary and sufficient for environmental deterioration to reach its nearly final point (not the final point, because some life is always present in industrial barrens).

The barren landscape presents itself not only to ecologists interested in the complex effects of manmade disturbance on ecosystems, but also to those involved with the determination of public policy related to environmental pollution (Anand et al. 2003). It is only rarely appreciated that severely contaminated sites and other post-industrial landscapes may support regionally rare and endangered species (Johnson et al. 1978; Eyre and Luff 1995). Furthermore, industrial barrens clearly show the results of ‘gross negligence’ typical for early stages of industrial development, and their exploration can serve to ecological education of people. Therefore our third goal is to briefly describe the diversity of life in industrial barrens and call for conservation measures.

Last but not least, we aimed at identification of knowledge gaps that require immediate attention of international scientific community, because most of existing industrial barrens may disappear rather soon due to strict emission control and rehabilitation measures. On the other hand, the serious concern is the potential for developing nations to repeat the environmental mistakes made by the developed world (Padgett and Kee 2004). The knowledge on mechanisms behind the development of industrial barrens may help to prevent habitat deterioration in developing countries, especially in South-Eastern Asia where

---

[1] Dumps of solid waste, as well as areas that became barren due to mechanical removal of soil (e.g. in the course of open-pit mining) are not considered here.

industrial emissions are predicted to increase drastically (Fowler et al. 1999).

2 Terminology

To our knowledge, no attempt was made to unify the terminology associated with description of the habitats severely disturbed by aerial emissions; terminology used by different researchers is summarised in Table 1. McCall et al. (1995, p. 847) defined ‘barrens’ adjacent to Sudbury smelters as landscapes ‘‘characterised by bare and sparsely vegetated land, severely eroded and blackened hilltops and acidic (pH < 4.0) and metal contaminated soils’’. Later on, McCall et al. (1995, p. 849) introduced a 5% vegetation cover to delineate barrens by using aerial photographs; Eränen and Kozlov (2006) used 10% cover to define industrial barrens. However, these absolute values may appear misleading in landscapes with naturally low vegetation cover, like deserts.

In this paper we classify as industrial barrens the bleak open landscapes evolved around the point sources of industrial pollution due to deposition of airborne pollutants, with small patches of vegetation (cover usually reduced to 10% or less relative to control) surrounded by bare land with illuvial horizon or even the rock exposed due to intensive soil erosion (relict soil cover usually less than 20%) (Figs. 1–3).

Industrial barrens are usually surrounded by strongly modified ecosystems (Figs. 4–6) that have a potential to turn into industrial barrens under some circumstances (see below). In Sudbury, these habitats where ‘‘conifers are generally absent and the forest consists of a near monoculture of stunted and coppiced white birch (*Betula papyrifera*)’’ were defined as ‘semi-barren’ area (McCall et al. 1995, p. 847) or described as ‘savannah woodland’ (Courtin 1994). Similar habitats existing around Monchegorsk and Nikel were termed ‘birch transitional community’ (Kozlov 2001, 2002) or ‘birch woodlands’ (Kozlov et al. 2001); some Russian authors (e.g. Stepanov and Chernenkova 1989) used an expression ‘forests with dead field layer vegetation’ for secondary birch regrowth near the Karabash smelter (Fig. 6).

3 Documented occurrence of industrial barrens

3.1 Responsible industries

We were able to obtain some information on 36 industrial barrens worldwide (Table 1). Nearly all of them (33 of 36) have developed in the impact zones of non-ferrous smelters and refineries, primarily those of copper-, nickel-, zinc- and lead-producing factories. The notable exceptions are the iron sintering plant in Wawa, Canada and the magnesite plants in Satka (Russia) and Lubenik (Slovakia). Industrial barrens are frequently associated with the historical smelting sites: 12 of them occur around industries that started operations in 18–19th centuries (Table 1). The most recent installation that caused development of industrial barrens is Ventanas smelter in Quinteros, Chile (operated since 1964).

Intriguingly, industrial barrens have not been observed around aluminium factories, which emit (or have emitted in the past) large amounts of phytotoxic compounds, primarily fluorine. Only Gilbert (1975, p. 120) mentioned that ‘‘very small areas of exposed rocky ground were at the denuding stage with eroding soils sparsely colonised by annuals’’ around two of three aluminium smelters in Norway. Recently, even the most exposed sites near the Bratsk aluminium factory in Siberia are covered by damaged and dwarfed forest with dense field layer vegetation (pers. obs.). Similarly, environmental impact of power plants, even the largest ones that emit more sulphur dioxide than some of smelters surrounded by barren lands (Pearce 1994), is not strong enough to cause development of industrial barrens.

In general, industrial barrens represent a relatively rare phenomenon: they were recorded around approximately 10% of point polluters which impact on biota was scientifically documented (by 2003, we retrieved the published information on biotic effects of 233 polluters: Kozlov and Zvereva 2003).

Fig. 1 Sudbury, non-reclaimed industrial barren (2001)

Fig. 2 Nikel, industrial barren developed from Scots pine forest (2000)

Fig. 3 Zapolyarnyy, industrial barren developed from birch woodland on a bog (2000)

3.2 Geographical distribution and vegetation zones

Nearly a half of identified 36 industrial barrens, including those at incipient stages of development

Fig. 4 Revda, erosion of bare soils (2002)

Fig. 5 Krompachy, secondary forest on bare ground behind the smelter (2001)

Fig. 6 Karabash, secondary birch forest on bare ground (2002)

(Table 1), occur in North America, with nine localities in USA and five in Canada. Russia houses 10 industrial barrens, three of which are located in the Kola Peninsula and six in Southern Ural region. The only industrial barrens in the Southern hemisphere are reported from Chile

Table 1 Documented occurrence of industrial barrens and dying forests on a barren soil (alphabetical order, by location)

Location		Polluter (establishment-closure)	Primary vegetation	Terminology used to describe the most disturbed landscapes	First record of industrial barrens	Barren/semi-barren area, ha (year of estimation)	Contributing disturbances and secondary stressors	References
Site	Country							
Anaconda	USA	Cu smelter (1884–1980)	Subalpine lodgepole pine and Douglas fir forest	Sites devoid of vegetation; nearly barren	Early 1900s	4,500/- (1992)	Unfertile soil; extreme climatic fluctuations	Haywood (1910), Galbraith et al. (1995), Marty (2000), Burt et al. (2003)
Ashio	Japan	Cu smelter (1877–1988)	Beech and coniferous forest	Biologically destroyed area; devastated area; absolute wasteland	1893	1,395/- (1893) >2,500/- (1970)	Logging; soil erosion	Usui and Suzuki (1973), Shoji and Sugai (1992)
Banská Štiavnica	Slovakia	Pb and Cu smelters (1750–1969)	Oak-hornbeam forest	Entirely destroyed plant cover; emission gaps; bare lands	1880s	<10/- (1970s)/-	–	Kapusta and Múdry (1974), Banásová et al. (1987)
Ducktown (Copperhill)	USA	Cu smelter (1854–1912)	Hardwood forests	Barren, eroded landscape; totally bare area/lightly vegetated zone; desert; denuded area; moonscape; blighted land	1870s(?)	2,700/6,800 (1910) 13,000/- (1930s) 2,833/19,020 (early 1940s) 930/- (1986)	Logging; fuel procurement; grazing by cattle; fire; soil erosion	Seigworth (1943), Hursh (1948), Teale (1951), Quinn (1989)
Flin Flon	Canada	Cu–Zn smelter (1930-)	Mixed boreal forest	Barren soil; a barren tract of rocky hills, parched soil and sparse vegetation	1970s?	–	–	Hogan and Wotton (1984), Winterhalder (2000, 2003), Lees (2000)
Garfield	USA	Cu smelter (1906-)	Coniferous forest and brush community	Extremely denuded areas; highly disturbed zone	Before 1970	1,500/- (1970)	Fire; soil erosion	Eastmond (1971)
Harjavalta	Finland	Cu–Ni smelter (1945-)	Southern boreal Scots pine forest	Understorey vegetation is almost completely absent; clonal dwarf shrubs have survived in small patches	1970s?	<50/- (2000)	–	Salemaa et al. 2001; pers. obs.

Table 1 continued

Location		Polluter (establishment-closure)	Primary vegetation	Terminology used to describe the most disturbed landscapes	First record of industrial barrens	Barren/ semi-barren area, ha (year of estimation)	Contributing disturbances and secondary stressors	References
Site	Country							
Henryetta	USA	Zn, Cd roaster/ smelter (1916–1968)	Oak forest	Completely denuded area; bare area	1970s	400/- (1960s)	–	Pancholy et al. (1975)
Karabash	Russia	Cu smelter (1907-)	Southern taiga	Industrial barren, industrial desert	1930s	<1,000/- (2002)	Soil erosion	Stepanov and Chernenkova (1989), Makunina (2002), E. Vorobeichik (pers. comm.) pers. obs.
Kellogg	USA	Pb smelter (1916–1980), Zn plant (1928–1980)	Cedar-hemlock forest	Barren hillsides; denuded area	1970s	7,285/- (1977)	Fire	Carter et al. (1977), Hansen and Mitchell (1978), Winterhalder (2000)
Kirovgrad	Russia	Cu smelter (1912-)	Southern taiga/ Scots pine forest	Complete destruction of ecosystems; industrial desert	1930s?	<100/- (1994)/-	–	Vorobeichik et al. (1996), E. Vorobeichik (pers. comm.)
Krasno-uralsk	Russia	Cu smelter (1932-)	Southern taiga/ Scots pine forest	Industrial desert	Early 1950s	<300/- (1980s)	–	Makhnev et al. (1990), E. Vorobeichik (pers. comm.)
Krompachy	Slova-kia	Cu smelter (1843-)	Mixed forests (Scots pine, beech)	Total degradation; bare soils; emission gaps (*imisne holiny*, Slov.)	1980s	<50/- (2002)	Soil erosion	Maňkovská (1984), Banásová and Lackovičová (2004), pers. obs.
Legnica	Poland	Cu smelter and refinery (1953-)	Arable land; remnants of oak – hornbeam or Scots pine forest	Waste land; bare ground with patchy ruderal vegetation	1980s	300–200/- (1990)	Soil erosion	Weber (2002), Lehmann and Rebele (2004)
Lubenik	Slovakia	Magnesite plant (1958-)	Broadleaved forest	Seriously damaged zone: no vegetation found; emission gaps	Mid-1970s	200 (2006)		Kautz et al. (2001), J. Kulfan and P. Zach (pers. comm.)
Maatheide/ Lommel	Belgium	Zn smelter (1904–1974)	Heath developed from agricultural landscape	Bare industrial area; desert-like area	Before 1940	450/- (1942) 98/- (1952) 135/- (1990)	–	Vangronsveld et al. (1995, 1996, pers. comm.)
Miami-Globe	USA	Two Cu smelters (1890–1924; 1915-)	Desert and desert grassland		1970s	<500/- (1976)	Overgrazing	Dawson and Nash (1980)

Table 1 continued

Location		Polluter (establishment-closure)	Primary vegetation	Terminology used to describe the most disturbed landscapes	First record of industrial barrens	Barren/semi-barren area, ha (year of estimation)	Contributing disturbances and secondary stressors	References
Site	Country							
Mednogorsk	Russia	Cu smelter (1939-)	Steppe	Industrial wasteland; gas-induced barren area	Prior 1980s	<500/- (1976)	Soil erosion	Shilova and Lukjanets (1989)
Monchegorsk	Russia	Ni–Cu smelter (1939–1941, 1947-)	Boreal coniferous forest	Industrial desert; zone of total destruction of ecosystems; industrial barrens; industrially created wasteland	Early 1960s	21,000/ 44,000 (1990s)	Logging; fire	Doncheva (1978), Kryuchkov (1993), Barcan and Kovnatsky (2002), V. Barcan (pers. comm.)
Murgul	Turkey	Cu smelter (1902- mid-1970s)	Coniferous and broadleaved forests	Area with almost no live plants	1960s	<1,000/- (1967)	Soil erosion; forest pests	Acatay (1968)
Nikel	Russia	Ni–Cu smelter (1932-)	Boreal coniferous forest/birch woodland	Industrial barrens	1960s	13,600/- (1973) 30,900/- (1999)	Fire	Tømmervik et al. (2003, pers. comm.)
Norilsk	Russia	Ni smelter (1939-)	Sparse larch forests, shrubby tundra	Dead forests; lichen desert; de-vegetated zone	Mid-1950s	-/- (total 300,000) (1980s); -/- (total > 400,000) (1990s)	Logging; forest diseases; fire	Filipchuk and Kovalev (1990), Vlasova and Filipchuk (1990), Kharuk (2000)
Palmerton	USA	Zn smelter (1898–1980)	Oak-chestnut-white pine forest	Completely barren or sparsely vegetated area; a barren, devastated, biological desert	1930s	485/- (1970s) >800/- (1980s)	Logging; fire; soil erosion; desiccation	Jordan (1975), Sopper (1989)
Quinteros	Chile	Cu smelter (1964-)	Shrubby grassland	The barrens	Mid-1970s	2,000/- (2005)	–	Ginocchio (2000, pers. comm.)
Queenstown	Australia	Cu smelter (1895–1969)	Forest of King Billy pine	Bare area; devoid of vegetation/substantially denuded; wasteland; deserted moonscape	By 1900	1,500/2,500 (1950s)	Logging; burning of the surface duff	Hodgson et al. (2000), Winterhalder (2000; Anonymous (2005a)
Redding	USA	Cu smelter (1860–1907)	Pine forest	All vegetation entirely dead	Early 1900s	1,000–1,500/- (1900s)	–	Haywood (1905, 1910)
Revda	Russia	Cu smelter (1940-)	South taiga/ Scots pine forest	Gas and smoke induced wasteland; industrial barren; industrial desert	Early 1950s	<100/- (1990s) <300/- (2000s)	–	Menstchikov et al. (1997), E. Vorobeichik (pers. comm.)

Table 1 continued

Location		Polluter (establishment-closure)	Primary vegetation	Terminology used to describe the most disturbed landscapes	First record of industrial barrens	Barren/ semi-barren area, ha (year of estimation)	Contributing disturbances and secondary stressors	References
Site	Country							
Satka	Russia	Magnesite plant (1900-)	Scots pine forest	Magnesite desert	1957	2,200/- (1957) 4,000/- (1959) 4,400/- (1963)	Grazing; forest pests; soil erosion	Kulagin (1964), Sokolov (1996)
Sudbury	Canada	Ni–Cu smelter (1888-)	Mixed boreal coniferous forest	Barren land/semibarren woodland; micro-desert; totally denuded barrenlands; badly devastated area	1920?	19,565/ 83,796 (1970)	Logging; burning of the surface duff; fire, pests, soil erosion, frost	Hazlett et al. (1983), Allum and Dreisinger (1987), Courtin (1994), McCall et al. (1995, Winterhalder (2000), Anand et al. (2003)
Superior	USA	Cu smelter (1924–1971)	Shrubby desert	[Some components of vegetation] almost entirely absent	1960s	–	Grazing	Wood and Nash (1976)
Szopienice	Poland	Zn smelter (1834-)	Scots pine forest	Industrial desert	Late 1960s	–	–	Wolak (1970)
Trail	Canada	Pb–Zn smelter (1896-)	Mixed forest	Drifting sand dunes	1930s	–	Logging, fires	Dean and Swain (1944), Winterhalder (2000), Nielsen and Kovats (2004)
Wawa	Canada	Iron sintering plant (1939–1998)	Mixed boreal coniferous forest	Very severe damage; total kill/heavy kill areas; fume kill area	1950s	13,870/- (1960) 10,850/ 19,100 (1970)	Fire, soil erosion	Gordon and Gorham (1963), Linzon (1975), McGovern (1975), Anonymous (1999)
Yellowknife	Canada	Au smelter (1941–1999)	Open sub-arctic woodland	Drastic deterioration	1970s	<800/- (1970s)	Fires	Hocking et al. (1978)
Ykspihlaja	Finland	Zn smelter (1962-), fertiliser and chemical plants (1940-)	Scots pine forest	Almost desert area; no forest floor vegetation; devegetated area	1970s	10/40 (1984)	–	Väisänen (1986), pers. obs
Zapolyarnyy	Russia	Ni–Cu ore roasting plant (1959-)	Birch woodland	Industrial barrens	Late 1960s	20,400/- (1973) 37,800/- (1999)	–	Tømmervik et al. (2003, pers. comm.)

and Tasmania. Industrial barrens have not been described from the tropics, and it can only be guessed whether this reflects geographical distribution of smelting activities, shortage of information or higher resistance of tropical ecosystems to extreme deposition of aerial pollutants.

Most of industrial barrens (27 of 36) occur in forested areas, where they generally replace coniferous or mixed forests. Barrens around Legnica, Poland, and Maatheide, Belgium, evolved from arable lands that were earlier covered by broadleaved forests. Similarly, smelter in Banská Štiavnica was earlier surrounded by oak-hornbeam forest. Industrial barrens near Zapolyarnyy, Norilsk and Yellowknife developed at the northern tree limit from sparse sub-tundra forests, birch woodlands and shrubby tundras. Barrens near Quinteros, Superior and in the Miami-Globe area are surrounded by shrubby grasslands and desert, while barrens at Mednogorsk developed from steppes.

3.3 Landscapes

Majority (27 of 36) of industrial barrens occur in the mountainous or hilly areas. However, since ore deposits are often associated with mountains, additional data are necessary to test the hypothesis that mountain landscapes are especially prone to severe disturbance caused by smelter fumes. Industrial barrens in relatively flat regions, like at Legnica in Poland, Harjavalta and Ykspihlaja in Finland, and at Maatheide in Belgium, seems less extensive, possibly due to less intensive soil erosion on planes.

Development of industrial barrens in mountain landscape can be enhanced by local meteorology. Fumes emitted by the lead and zinc smelter at Trail drifted north and south along the relatively narrow, mountain-bordered valley that constitutes a natural channel for the smelter gases (Archibold 1978; Quinn 1989). The prevailing north-westerly winds carry emissions of Palmerton smelter directly toward Blue Mountain, resulting in higher concentrations of pollutants than would be the case in level terrain (Jordan 1975). Similarly, predominance of meridional winds in surroundings of Monchegorsk caused development of extensive industrial barrens to both North and South of the nickel–copper smelter (Doncheva 1978; Kryuchkov 1993); at the same time, nearly undamaged Scots pine (*Pinus sylvestris* L.) forest still occurs some 5 km East of the smelter (pers. obs.).

Mountains can not only channel aerial emissions but also 'trap' the smoke, greatly enhancing vegetation exposure and the resulting damage. For example, the Copper Basin, comprising 3,300 ha, is surrounded by a rim of mountains (Wolt and Lietzke 1982). The Summer Valley near the Anaconda smelter "resembled a bowl, rimmed on three sides by the main range of the Rocky Mountains... During the winter months, and occasionally in the summer, an inversion often placed a lid over the valley and trapped the city's smoke..." (MacMillan 2000, p. 25). Inversion conditions occur frequently near the Kellogg smelter in the fall (Ragaini et al. 1977); similarly, local contamination by nickel–copper smelters at Nikel and Monchegorsk is exacerbated by frequent temperature inversions (Kryuchkov and Makarova 1989).

3.4 Topography

Topography has an important effect on spatial pattern of both vegetation decline and recovery (Easmond 1971; Usui and Suzuki 1973; Gilbert 1975). In Sudbury, the line of vegetation discontinuity usually followed elevation contour lines (McCall et al. 1995). Exposed hilltops were particularly prone to fumigation damage in the past (James and Courtin 1985), and are now very slow to recover (McCall et al. 1995). Hilltops in Sudbury remain bare for decades after emission decline, and their sparse soils are still subject to erosion (Dudka et al. 1995). In industrial barrens near Monchegorsk vegetation damage was lower, and vegetation cover and species richness were higher in the bottom of the valley, near the small stream, compared with slopes that were only some 50–80 m above (Kozlov 1997).

4 Development of industrial barrens

4.1 Effects of pollutants

The largest air pollution problems in industrial barrens are episodic, with high ambient concentrations lasting a few hours to two days (Sivertsen et al. 1994). Near the smelters in the Kola Peninsula these episodes in 1980s occurred during 3–5% of days in winter and 1–2% in summer (Baklanov and Sivertsen 1994). During episodes, hourly concentrations of SO_2 reached 1200 μg m^{-3} near Monchegorsk (Baklanov and Rodyushkina 1993), 2500 μg m^{-3} near Nikel (Sivertsen et al. 1994), and 14,800 μg m^{-3} near Norilsk (Savchenko 1998). During the summer of 1994, monthly average concentrations of SO_2 in industrial barrens near Monchegorsk were 150–270 μg m^{-3} (Zvereva and Kozlov 2005, and unpublished). These values should be regarded intolerable for local forests, because the proposed SO_2 critical levels estimated by different methods range 5–15 μg m^{-3} as a growing season mean (Manninen and Huttunen 1997).

Although acute damage by sulphur dioxide, the main phytotoxic component of smelter fumes, definitely contributed to vegetation decline (e.g. Haywood 1910; Euler 1939; Makhnev et al. 1990), the importance of this damage for the development of industrial barrens remains unclear. Extreme levels of sulphur dioxide, especially near the roastbeds, killed adjacent forests during relatively short time (Hedgcock 1912; Dean and Swain 1944; Gordon and Gorham 1963; Kryuchkov 1993; Hutchinson and Symington 1997). However, absence of industrial barrens around power plants and aluminium smelters hints that development of this kind of landscape is impossible without severe soil contamination by heavy metals (see Sect. 5.1). In particular, near Anaconda smelter, percent bare ground positively correlated with both concentrations of hazardous substances in soil and soil phytotoxicity revealed by laboratory experiments, thus suggesting the leading role of soil contamination in loss of vegetation in the field (Galbraith et al. 1995).

4.2 Accompanying disturbances

Smelting industry was usually preceded by or accompanied with other human-induced disturbances, which share the responsibility for the development of industrial barrens. In many historical smelter sites (e.g. Kellogg, Sudbury, Copper Basin, Queenstown, Ashio) deforestation was primarily due to harvesting for mine timber and fuel (Usui and Suzuki 1973; Hansen and Mitchell 1978; Winterhalder 2000). Shortage of fuel for smelters in the Copper Basin was noticed as early as in 1861; by 1878, about 130 km^2 had been stripped of vegetation (Anonymous 2005b). Some 3,262,000 m^3 of wood were consumed for roasting in Sudbury between 1890 and 1930 (Allum and Dreisinger 1987). Similarly, over 3 million tonnes of timber were cut down around Queenstown between 1896 and 1923 (Anonymous 2005a).

When commercial forests started to die due to pollution impact, the very first reaction of the foresters was to cut down the damaged stands in order to prevent losses of timber. This practice was widely applied in Central and Northern Europe (e.g. Gilbert 1975) until at least the mid-1970s, when it became obvious that the cost of harvested timber is minor in relation to the costs of rehabilitation measures required after clear-cutting. In spite of this knowledge, some local regulations (existing, for example, in Russia) still require immediate felling of pollution-damaged forest in order to make use of the timber (Kozlov 2004). Alternatively, dead trees can be removed to make the landscape more 'attractive' visually; in spite of advice of the local scientists, this selective logging was conducted in spring of 2006 near the Monchegorsk smelter (pers. obs.). However, the polluted forest never become completely dead, and even the dead trees maintain some climatic and biotic stability in the contaminated habitats, in particular by ameliorating microclimate (Wołk 1977) and preventing soil erosion. The old clearcuts under severe pollution impact near both Monchegorsk and Nikel have been rapidly transformed to industrial barrens, while some vegetation in the adjacent uncut areas is still alive (Kozlov 2004).

Industries build in 1920–1940s did not require so much of timber as a fuel. Still forests were cut for building purposes, e.g. around Monchegorsk. Initial deforestation around Norilsk, Siberia, was caused by quite peculiar reasons: since prisoners were used extensively for the construction of the Norilsk industry, a buffer of 3–4 km in width was cut around each of prison camps (Kharuk 2000). Importantly, logging causes soil disturbance that may facilitate erosion.

Forests with unusually open canopies, like one observed near Palmerton smelter in 1970s (Jordan 1975), or forest with stunted trees and dead or nearly dead ground layer vegetation, recently existing e.g. near Krompachy, Harjavalta, Ykspihlaja, Revda and Karabash smelters (pers. obs.), seem to represent a transitional stage between forests and industrial barrens. For example, field layer vegetation cover near Harjavalta is ca. 5%, while cover of Scots pine remains as high as 44% (Salemaa et al. 2001). This kind of forest may gradually turn to industrial barrens; however, it is likely that most, if not all, industrial barrens evolved following a fire that destroyed remnants of forest or shrubby vegetation. In semi-barren and barren sites near both Monchegorsk and Nikel we have observed several highly localised fires that consumed woody debris and destroyed most of remaining vegetation, leading to the extension of the barren area. We suppose that dying forests around the smelters listed above will immediately turn into industrial barrens following a fire, because a natural post-fire regeneration is hampered by soil toxicity and altered microclimate (Jordan 1975; Hansen and Mitchell 1978; Vajda and Venäläinen 2005). The detrimental role of occasional forest fires was considered the primary reason of forest deterioration around Bell Bay aluminium smelter in Australia, mostly due to disruption of nutrient cycles and alteration of soil moisture regime (Mitchell 1982).

Both logging and forest damage by fumes from smelting and roasting increased the amount of woody debris in the impacted areas, making them especially vulnerable to occasional fires. Unusually large amount of woody debris is clearly seen on photographs taken in the vicinity of several smelters (Figs. 1–3). In Sudbury, not only sparks from wood-burning locomotives of the Canadian Pacific Railway started the fires, but also prospectors often burned the remaining vegetation and duff to reveal the bedrock below (Winterhalder et al. 2001). In Palmerton, hillside vegetation behind zinc plant was originally destroyed by fire (Pommerening 1977). In the Copper Basin, in times of dry weather, almost daily fires swept the earth bare of vegetation (Teale 1951). The degradation of the Copper Basin landscape may have been further exacerbated by lowland farmers, who trucked cattle into the Basin for free grazing, and regularly burned the land to encourage growth of a sparse pasture (Clay 1983).

4.3 Hampering of natural recovery

All catastrophic events that destroy vegetation, like fires or avalanches, are always followed by natural recovery that, sooner or later, results in restoration of about the same vegetation community. The extant plants growing in industrial barrens may sustain extreme pollution loads and produce viable seeds, sometimes even in larger amounts than in unpolluted sites (Zvereva and Kozlov 2001, 2005; Kozlov and Zvereva 2004). These seeds preserved in the soil seedbank remain viable for decades (Komulainen et al. 1994); still natural regeneration is absent or nearly absent in industrial barrens (Jordan 1975; Kozlov and Haukioja 1999; Rigina and Kozlov 2000). This is most likely due to high concentrations of heavy metals in uppermost soil layers (Table 2) that stunted radicle growth of many plant species (Stavrova 1990; Zeid 2001). Although seeds of several native plant species were capable of germinating in soils of industrial barrens at both Sudbury and Monchegorsk, root growth was so inhibited that seedlings quickly dried off and died completely (Winterhalder et al. 2001; Kozlov 2005). Persistence of some plants in industrial barrens may be transient, being explained not only by higher resistance of the survivors, but also by past phenotypic acclimatisation of mature plants to gradual increase in pollution (Kozlov 2005), and the extent of industrial barrens increases as plants age and die (Zverev and Kozlov, unpublished).

Additional problems for vegetation recovery may be imposed by slow decomposition of litter. This was in particular noticed around the Palmerton smelter, where a considerable portion of the area is covered with a layer of undecomposed tree bark (Sopper 1989) or by thick (6–16 cm) litter (Jordan 1975). Similarly, leaf litter is the major problem of semi-barren communities in Sudbury, because it hinders the establishment of understorey species by seeds (Winterhalder 2000).

Table 2 Chemistry of humus layer or uppermost soil horizon in industrial barrens

Location	Extreme pH	Maximum concentrations of contaminants, μg g^{-1}						Minimum level of nutrients, mg g^{-1}		References
		Cu	Cu[a]	Ni	As	Zn	Pb	N	Ca	
Anaconda	3.0	2,800	–	14	408	849	474	2.30	–	Swain and Harkins (1908), Galbraith et al. (1995), Marty (2000), Redenteet al. (2002), Burt et al. (2003)
Ashio	4.3	–	–	–	–	–	–	0.37	0.17	Usui and Suzuki (1973)
Banská Štiavnica	4.5	770	–	–	130	4,000	18,000	3.22	0.56	Banásová et al. (1987)
Ducktown	3.2	–	–	–	–	–	–	–	0.02	Wolt and Lietzke (1982)
Flin Flon	4.4	2,670	–	130	558	7,428	1692	–	–	Henderson et al. (1998)
Garfield	3.7	–	–	–	–	–	–	–	–	Eastmond (1971)
Harjavalta	3.5	49,000	7,540	913	58	620	204	–	1.17	Helmisaari et al. (1995), Derome and Nieminen (1998), Uhlig et al. (2001), Salemaa et al. (2001), Nieminen et al. (2002), Nieminen (2004)
Henryetta	5.0	–	15	–	–	19,510	2,450	0.23	–	Pancholy et al. (1975), Basta et al. (2001)
Karabash	–	6,744	–	>10,000	1,500	10,000	3,000	–	–	Chernenkova (2002), Makunina (2002)
Kellogg	3.9	>400	–	>2,000	260	29,000	7,900	0.50	–	Ragaini et al. (1977), Hansen and Mitchell (1978)
Kirovgrad	4.1	3,758	4,040	–	162	3,689	674	–	–	Marin (1996), Vorobeichik (2003, 2004)
Krasnouralsk	2.2	1,611	–	3,216	–	1,696	1,725	–	–	Menshchikov et al. (1997)
Krompachy	4.0	8,437	–	25	130	1,482	3,343	–	–	Maňkovská (1984), Wilcke et al. (1999) Banásová and Lackovičová (2004)
Legnica	4.4	15,443	33	33	–	5,000	7,000	0.10	–	Rebele et al. (1993), Rybicka and Jędrzejczyk (1995), Weber (2002), Lehmann and Rebele (2004)
Lubenik	9.2	10	–	30	–	70	38	0.50	0.13	Šály and Mihálik (1985), Kautz et al. (2001), Tucekova (2001)
Maatheide	5.6	1,650	–	–	–	11,425	1800	–	–	Vangronsveld et al. (1995, 1996)
Mednogorsk	3.3	5,000	–	–	–	4200	1250	–	–	Lurie (1986), Shilova et al. (1984), Shilova and Lukjanets (1989)
Miami-Globe	4.0	2,183	2,250	–	–	67	90	–	–	Dawson and Nash (1980)
Monchegorsk	3.9	4,622	1,268	9,288	41	210	88	0.15	0.02	Lukina and Nikonov (1996, 1999); Barcan and Kovnatsky (1998), V. Barcan (pers. comm.)
Murgul	–	–	–	–	–	–	–	–	–	<No data found>
Nikel	3.7	3,489	113	2,990	–	113		–	0.02	Lukina and Nikonov (1996)
Norilsk	4.4	20,600	–	7147	–			–	–	Igamberdiev et al. (1994), Kharuk et al. (1996), Gorshkov (1997)

Table 2 continued

Location	Extreme pH	Maximum concentrations of contaminants, μg g^{-1}						Minimum level of nutrients, mg g^{-1}		References
		Cu	Cu[a]	Ni	As	Zn	Pb	N	Ca	
Palmerton	4.5	2,390	0.69	33	–	135,000[a]	5,225	–	–	Buchauer (1973), Beyer et al. (1985), Sopper (1989), Kelly and Tate (1998)
Quinteros	6.2	3,718	110	–	–	174	105	0.50	–	Ginocchio (2000), Ginocchio et al. (2004)
Queenstown	–	–	–	–	–	–	–	–	–	<No data found>
Redding	–	–	–	–	–	–	–	–	–	<No data found>
Revda	2.9	9,585	12,120	–	–	4,194[a]	2,348[a]	–	–	Vorobeichik (2003, pers. comm.)
Satka	9.0	–	–	–	–	–	–	–	–	Sokolov (1996)
Sudbury	2.0	9,700	900	12,300	–	336	92	0.99	0.60	Hutchinson and Whitby (1974), Hazlett et al. (1983), Dudka et al. (1995), Hutchinson and Symington (1997), Winterhalder (2000), Anand et al. (2003)
Superior	5.0	9,618	–	–	–	299	323	–	–	Wood and Nash (1976)
Szopienice	6.3	247	–	–	–	24,400	3,500	–	–	Badora et al. (1998)
Trail	3.7	106	–	67	157	1,632	7,490	0.30	–	Goodarzi et al. (2002), Nielsen and Kovats (2004)
Wawa	–	110	–	62	935	165	120	–	1.25	Anonymous (1999)
Ykspihlaja	–	–	–	–	–	–	–	–	–	<No data found>
Yellowknife	4.0	130	–	–	21,213	500	110	–	–	Hocking et al. (1978), Hutchinson et al. (1982), Anonymous (2003)
Zapolyarnyy	3.2	1,020	186	2,230	–	–	–	–	0.01	Niskavaara et al. (1996), Reimann et al. (1998), T. Gorbacheva (pers. comm.)

[a] Plant available forms

[b] In isolated patches of decomposed leaf litter; uppermost soil layer contained 50,000–80,000 μg g^{-1} (Buchauer 1973)

4.4 Soil erosion

The soil of developing industrial barrens, having lost its protective vegetation cover, suffers from extensive erosion (Figs. 4, 5). Sparsely vegetated sites near Anaconda smelter are mostly devoid of topsoil (Marty 2000); soil erosion is especially severe on steep slopes (Redente and Richards 1997). The topsoil, and sometimes even the subsoil, have been lost in Ducktown (Seigworth 1943), Queenstown (Anonymous 2005a), Monchegorsk (Kryuchkov 1993), Nikel (Fig. 2), Zapolyarnyy (Fig. 3), Palmerton (Jordan 1975), Karabash (Stepanov and Chernenkova 1989), Ashio (Usui and Suzuki 1973) and several other sites. Even after emission decline, soil is still exposed to water erosion by runoff, summer desiccation, wind erosion and frost heaving (Hazlett et al. 1983; Dudka et al. 1995; McCall et al. 1995; Vangronsveld et al. 1995).

In contrast to dying forests with large amount of litter, erosion of bare ground is exacerbated by the intense frost-heaving and needle ice formation that resulted once the insulating leaf litter was gone (Winterhalder et al. 2001). As the result, soils of industrial barrens around Sudbury (Fig. 1), Monchegorsk, Nikel (Fig. 2), Palmerton, Karabash, and some other polluters have a stony covering (Sopper 1989; Winterhalder 2000; pers. obs.). These eroded lands are unlikely to revegetate naturally (Jordan 1975), and transformation of forests into industrial barrens has sometimes been claimed to be irreversible (Tsvetkov 1991), at least on the time scale of the human life span. In particular, the natural revegetation had not occurred in industrial barrens adjacent to Palmerton smelter for at least 50 years (Sopper 1989). Heavily contaminated sites at Maatheide in Belgium remained bare some 20 years following the closure of zinc smelter (Vangronsveld et al. 1995). Similarly, no regrowth appeared until 2006 in industrial barrens surrounding the Monchegorsk smelter (pers. obs.), although emissions of both sulphur dioxide and heavy metals drastically declined in early 1990s.

4.5 Positive feedbacks

In many cases initial (partly pollution-induced) forest disturbance causes secondary effects (like increased snow evaporation, followed by soil freezing and plant damage) that may enhance further disturbance in a positive feedback fashion (Kozlov 2001, 2002). Forest decline results in higher wind speed (see Sect. 5.3) that may enhance environmental stress via changes in snowpack structure. A thin and compact snow layer explains the lower soil temperatures recorded in industrial barrens during the wintertime (Kozlov and Haukioja 1997) that in combination with a pollution-induced decrease in cold-hardiness of conifers (Sutinen et al. 1996) increases the probability of death of extant trees from freezing injury. Importantly, climatic effects of deforestation may hamper recovery of vegetation even in absence of pollution (Arsenault and Payette 1997; Vajda and Venäläinen 2005).

Extant plants in industrial barrens facilitate deterioration of soil quality in their own root-inhabited areas: plant foliage traps contaminants, which then enter the soil (with either rainfall or plant litter) immediately under a plant. As the result, copper concentration in organic soil under *Empetrum nigrum* L. patches near Harjavalta smelter (49,000 μg g^{-1}) was much higher than in surrounding barren soils (Uhlig et al. 2001). Similarly, in industrial barrens near Monchegorsk mean concentrations of plant-available nickel and copper in topsoil were higher under dwarf shrub patches than in bare areas (Zvereva and Kozlov 2005, and unpublished), and concentrations of several pollutants were higher under extant trees than in between-tree gaps (Lukina and Nikonov 1996).

Loss of biodiversity and creation of monoculture on semi-barren areas, such as birch woodlands near Sudbury and Monchegorsk, can increase population densities of pests and pathogens (see Sects. 6.1–6.3) which damage or even kill the remaining vegetation, thus contributing to the expansion of industrial barrens. In particular, bronze birch borer (*Agrilus anxius* Gory) killed 60–90% of birch stems near Sudbury by 1990s (Courtin 1994). Death of chestnut from diseases was reported in the impact zone of the Palmerton smelter (Jordan 1975), although it remains unclear whether this disease was facilitated by forest damage by smelter fumes. Forest pests were reported to accelerate dieback of the remaining trees near the polluters at Satka (Kulagin 1964) and Murgul (Acatay 1968).

Due to these positive feedbacks, industrial barrens may be to a certain extent resilient to external impacts, including both emission decline and restoration efforts. By using Monchegorsk smelter as an example, Tarko et al. (1995) predicted extension of the zone of biotic damage during several years following complete ceasing of emissions. In agreement with this prediction, gradual decline of mountain birch populations in industrial barrens surrounding the Monchegorsk smelter continued at least until 2006, some 10–15 year after drastic emission decline (pers. obs.). This kind of resilience is best described by the 'alternative state' models of ecosystems that consider abrupt shifts between two or more ecosystem states and incorporate system thresholds and feedbacks (Suding et al. 2004).

4.6 Time frame

Development of industrial barrens may proceed rather fast: although the copper smelter in Queenstown was built in 1895 only, the combination of timber felling, the sulphur fumes and the heavy rainfall in the area (which washed away the top soil) ensured that already by 1900 the whole valley around Queenstown looked like a desert (Anonymous 2005a). Appearance of industrial barrens near Quinteros was first observed some 10 years after the Ventanas smelter started its operations (R. Ginocchio, pers. comm.) But in most of the documented situations, development of industrial barrens takes 20–35 years; this time span was reported for Sudbury, Trail, Monchegorsk, Ducktown, Anaconda and Palmerton smelters (Table 1).

5 Environmental conditions in industrial barrens

5.1 Soil toxicity

Soils of industrial barrens contain huge amounts of toxic pollutants deposited from aerial emissions. In all documented cases (Table 2), the concentration of at least one pollutant in decomposed litter or in uppermost soil layer exceeded 1,000 μg g^{-1} (i.e. 1 g of pollutant per 1 kg of soil), or at least approached this value (Wawa). The highest concentrations of pollutants exceeded 10,000 μg g^{-1}, with an absolute maximum of 135,000 μg g^{-1} of zinc near the Palmerton smelter (Buchauer 1973). These concentrations are much higher than the toxicity limits; however, the large (but highly variable—Table 2) fraction of metals is deposited in insoluble forms, such as oxides, and is therefore not readily available for plants and animals (Kozlov et al. 2000a). In spite of that, total rather than bio-available levels of pollutants are reported in most of studies (Table 2), although soil toxicity can not be judged from these total levels which therefore are only of limited value for ecotoxicology.

Since majority of heavy metals accumulated in soils are in non-soluble forms, their complete leaching from upper soil horizons will take centuries, e.g. 160–270 years for nickel and 100–200 years for copper accumulated in industrial barrens around Monchegorsk (Barcan 2002). It is estimated that mobilisation of metals stored in soils can sustain the high concentrations of copper and nickel in many lakes of the Sudbury basin for well over 1000 years (Nriagu et al. 1998).

Although soil acidification is often mentioned among principal reasons of vegetation damage or even decline, soils of industrial barrens are not always more acidic than soils of surrounding landscapes (Table 2). In some situations, the pattern may be even opposite: soils near Palmerton smelter are less acidic than in the background region, perhaps because of zinc oxide deposition (Jordan 1975). Similarly, soil pH near Vantanas smelter was 6.2 compared with 4.8 in background sites (Ginocchio 2000). Finally, soils around the magnesite plant at Satka are extremely alkaline (pH = 9), and development of industrial barrens was due to formation of thick (up to 10 cm!) cement crust preventing most of plants to grow (Kulagin 1964).

5.2 Soil nutritional quality

Although it is widely accepted that soil acidification promotes nutrient leaching from upper soil horizons, the data on soil nutritional quality are available only for some industrial barrens

(Table 2). In particular, exchangeable Ca, Mg and K near Harjavalta smelter are reduced by a factor of 3–5 compared to more distant sites (Mälkönen et al. 1999). Nitrogen near Monchegorsk is reduced by a factor of 10 or more (Lukina and Nikonov 1999). The loss of base cations from the organic layer close to the smelter is primarily due to displacement by copper and nickel (Derome and Lindroos 1998). Since fertilisation generally improved plant performance in industrial barrens (Winterhalder 2000), it is believed that nutritional deficiency is one of the factors adversely affecting plant life in these habitats. Recently, soil nutritional quality was demonstrated to be the leading factor influencing abundance and diversity of microorganism populations in Sudbury pollution gradient (Anand et al. 2003).

5.3 Microclimate

Disappearance of vegetation, especially of trees, strongly modifies the climate of industrial barrens. Although this problem is investigated insufficiently, it seems that the most important changes are imposed by altered temperature and wind regime. Even at early stages of pollution-induced forest deterioration air and soil temperatures during the growth season may substantially increase, leading to an increased water loss from upper soil layers (Wołk 1977). Air temperatures in industrial barrens near Ducktown in summer were 1–2° C higher and in winter 0.3–1°C lower than in surrounding undisturbed (forested) sites (Hepting 1971). Similarly, air temperatures in barren sites at Monchegorsk were 1–2° C lower in cool periods (under +7° C) and 1–2° C higher in warm periods compared to undisturbed forests some 20–30 km apart (Kozlov and Haukioja 1997). Daily fluctuations in temperatures of barren soils are much higher than in undisturbed sites where the heat exchange is buffered by vegetation (Hursch 1948; Wołk 1977; Kozlov and Haukioja 1997; Winterhalder 2000). The lack of leaf litter results in enhanced frost action, imposing additional stress on plants (Sahi 1983). Barren soils are overheated in summer (e.g. average soil temperature in barren sites at Ducktown were increased by 11°C; Hepting 1971), and this overheating is accompanied by fast loss of soil moisture (Hursch 1948; Teale 1951; Freedman and Hutchinson 1980; Courtin 1994; Kozlov and Haukioja 1997; Marty 2000; Winterhalder 2000); all these factors obviously influence plant performance. Lower amount of precipitation was reported from Ducktown (Hepting 1971) but not found at Monchegorsk (pers. obs.). Importantly, drought may enhance toxicity of some contaminants, e.g. zinc (Jordan 1975).

Wind speed, measured in industrial barrens adjacent to the copper smelter at Ducktown, was increased by a factor 5–15 (Hepting 1971), while around the nickel–copper smelter at Monchegorsk it was two to three times as high as in nearly unpolluted forests (Kozlov 2002). High winds and subsequent particle movement that can sand blast, bury, and defoliate plants, were reported to impose additional stress on heavily contaminated sites near both Anaconda and Monchegorsk smelters (Marty 2000; Kozlov 2001).

Along with the direct impact of wind on plant performance, higher wind speed is responsible for thin snow layer (about one-third of that in unpolluted forests) in industrial barrens around the Monchegorsk smelter (Kozlov 2001) which, in turn, results in lower soil temperatures during the winter time (Kozlov and Haukioja 1997). Both these factors increase exposure of plants to frost damage. Soil freezing (in autumn) occurred in industrial barrens near Monchegorsk 10–11 weeks earlier and soil thawing (in spring) 3–4 weeks earlier than in unpolluted forests (Kozlov and Haukioja 1997). Furthermore, a lower accumulation of snow in industrial barrens, in combination with higher wind speed, may expose plants to additional drought stress. However, snow cover in industrial barrens near Nikel has about the same depth as in unpolluted forests (Ratkin 1999), and therefore the generality of the effects discovered near Monchegorsk remains unknown.

6 Life in industrial barrens

6.1 Biodiversity

General loss of biodiversity with the replacement of undisturbed habitats by industrial barrens seems indisputable (e.g. Jordan 1975; Kleinert 1988; Courtin 1994; Koponen and Niemelä 1995;

Cicák et al. 1999); however, the magnitude of this effect had only rarely been documented. In the 'total kill' area around Wawa the ground flora declined to 0 to 1 species per 40 m^2 from about 20–40 species in unpolluted sites (Gordon and Gorham 1963). Similarly, grass communities at Garfield contained 1–5 species per 50 m^2 plot, compared to 7–22 species at most distant sites (Eastmond 1971). Near the Anaconda smelter, plant species richness in 1992–1994 was about one-third of control (Marty 2000). The number of plant species (observed in five 1-m^2 plots) on 10–50 m from the edge of the O'Donnell roast bed (Sudbury, Canada) 66 years after its closure ranged 5–7, compared to 25–31 species at the distances 150–300 m of it (Hutchinson and Symington 1997). In Miami, Arizona, grasses, forbs, and small shrubs were entirely absent at the site proximate, to the coppee smelter, whereas the cover of large shrubs had not been affected (Dawson and Nash 1980). The total floristic diversity near the Quinteros smelter was 17 species compared to 42 species in control sites (Ginocchio 2000).

In industrial barrens near Monchegorsk the number of vascular plant species ranged 0–25% of the number recorded in unpolluted (control) sites if censuses were made by using small plots (1–25 m^2). However, if larger plots (100–10,000 m^2) were surveyed, the decrease in species richness was around one-third, suggesting that pollution effects were expressed in decline of population densities rather than in selective removal of certain species (Kozlov et al. 1998, and unpublished).

Samples of moths and butterflies, as well as human-biting flies, collected in industrial barrens near Monchegorsk showed nearly the same diversity as samples from primary forests, although abundance of most species was drastically declined (Kozlov 1997; Kozlov et al. 2005a). Maximum species richness of ants in the Monchegorsk pollution gradient in 1993 was discovered in industrial barrens, whereas in 1994 it peaked in birch transitional communities surrounding the barren area (Kozlov 1997). This result is in line with findings by Koponen and Niemelä (1995) who reported higher species richness of ants in a barren site near the Harjavalta smelter than at more distant and less disturbed sites. Species richness of ground beetles (Carabidae) near the Lubenik magnesite plant was reduced to approximately one-third of observed in an unpolluted site (Kleinert 1988); however, rarefaction analysis shows that this difference was mostly due to differences in abundance, and actual species loss was much smaller, about 30% (Kozlov, unpubl.).

Some of insect species clearly prefer barrens to undisturbed habitats. In course of bait-trapping along the Monchegorsk pollution gradient, all the specimens of *Polia conspicua* (B.-H.), a mountain tundra noctuid moth, were collected between the external border of the industrial barrens and the smelter (Kozlov et al. 1996). Moreover, viable population of an extremely rare moth, *Sesia bembeciformis* (Hb.), the species considered extinct in Finland (Rassi et al. 1985), was discovered in an industrial barren south of Monchegorsk (Kozlov 1997). The buprestid beetle *Melanopila formaneki* (Jakobson) was for the first time discovered in Finland when studying Scots pines in a semi-barren site near the Harjavalta smelter (Heliövaara et al. 1990); the same site is also inhabited by several spiders which are missed from unpolluted forests (Koponen and Niemelä 1993). Industrial barrens may favour some life forms at the expense of others: for example, barrens near Lubenik magnesite plant were dominated by smaller ground beetles (Carabidae) with diurnal activity, whereas larger species with nocturnal activity were mostly associated with unpolluted habitats (Kleinert 1988).

In industrial barrens near Monchegorsk species richness of birds was reduced to approximately one third relative to unpolluted sites (Gilyazov 1993; Kozlov et al. 2005b). Near the magnesite factory in Lubenik the reduction in both species richness and abundance of breeding species seem even more pronounced (Cicák et al. 1999), although direct comparison is difficult due to different size of study plots. Among small mammals, only large-toothed redback vole (*Clethrionomus rufocanus* Sund.) and root vole (*Microtus oeconomus* Pall.) were captured near Monchegorsk whereas six species were recorded in undisturbed forests (Kozlov et al. 2005b). Winter censusing of large mammals in industrial barrens revealed tracks of two species, mountain hare (*Lepus timidus* L.) and red fox (*Vulpes vulpes* L.), compared with eight species in unpolluted areas (Kozlov et al. 2005b).

To conclude, species richness of plants and animals in industrial barrens in an average comprises one-third to one-half of the observed in surrounding undisturbed habitats. However, diversity of some groups is not affected, and some species occurring in industrial barrens are not found in undisturbed habitats.

6.2 Population density and structure

Microbiota of degraded soils had been shown to lose its resilience to disturbance and become no longer able to perform normal processes of cycling nutrients, assimilating organic residues and maintaining soil structure. As the result, in industrial barrens near Harjavalta accumulated mass loss of Scots pine needle and fine roots was ca. 80% of observed in unpolluted site (McEnroe and Helmisaari 2001), whereas near Sudbury decomposition of birch leaves was reduced to ca. 40% of the control level (Johnson and Hale 2004). This retarded decomposition results in particular in formation of thick matt of litter under extant plants (pers. obs.); this litter seems to mitigate adverse climatic effects on field layer vegetation (Zvereva and Kozlov 2007), but it can also hamper seedling establishment (Jordan 1975).

Although abundance of most species in industrial barrens is extremely low (e.g. Gilyazov 1993; Kozlov 1997; Salemaa et al. 2001; Vorobeichik 2003, 2004; Kozlov et al. 2005a, b), some plants and animals flourish in these habitats. In particular this concern some willow species that are much more abundant in barren sites than in unpolluted forests. Increase in willow density, along with decline of pressure from natural enemies, favours several insect herbivores. Willow-feeding leaf beetle, *Chrysomela lapponica* L., generally not abundant through its distribution range, in some years reached extremely high densities in industrial barrens near both Monchegorsk and Nikel (Zvereva et al. 2002). Also its specialised parasites, scuttle fly *Megaselia opacicornis* Schmitz and tachinid fly *Cleonice nitidiuscula* (Zett.), earlier known from a few specimens only, are abundant in industrial barrens near both Monchegorsk and Nickel (Richter and Zvereva 1996; Zvereva and Kozlov 2000a; Disney et al. 2001). Similarly, densities of birch- and willow-feeding leafrollers, along with some *Eriocrania* leaf-miners, in industrial barrens near both Monchegorsk and Nikel are on an average much higher than in unpolluted forests (Kozlov 1997, Zvereva and Kozlov 2006). The higher mean and peak densities of *Eriocrania* observed in industrial barrens are explained by disturbance of density-dependent feedback with parasitoids (Zvereva and Kozlov 2006).

Population structure of both plants and animals is considerably changed in industrial barrens. Populations of some woody species (mountain birch and willows in Monchegorsk, white birch in Sudbury) become more continuos due to elimination of pollution-sensitive competitors, while ground layer vegetation is highly fragmented (Zvereva and Kozlov 2004, 2007). In Sudbury, the dimension of patches of ‘micro-deserts’ and ‘micro-oases’ varies typically between 5 m and 15 m (Courtin 1994). In Monchegorsk, patches of ground layer vegetation are usually smaller, ranging 0.2–2 m in dimension, with barren gaps reaching as much as 20–50 m (pers. obs.). Absence of natural regeneration causes strong shift in age structure of plant populations. The average site-specific age of randomly collected individuals of *Empetrum nigrum* ssp. *hermaphroditum* (Lange ex Hagerup) Böcher in industrial barrens near Monchegorsk and Nikel was 34–38 years, compared with 17–28 years in undisturbed forests (V. Zverev and M. Kozlov, unpublished).

Populations of some insects, like leafmining *Eriocrania*, in industrial barrens became more aggregated than in unpolluted forests, possibly because strong winds force ovipositing females of these tiny moths to walk along a birch twig rather than take a risk of flying to another birch tree (Kozlov 2003; Zvereva and Kozlov 2006).

6.3 Growth form of woody plants

The trees which managed to survive in industrial barrens generally demonstrate bush-like or even creeping growth forms (Kryuchkov 1993; Kozlov and Haukioja 1995; Rigina and Kozlov 2000). In the most polluted barren sites near Monchegorsk height of mountain birches was in an average nearly 10 times lower than in healthy forests (Kozlov 2001). Similarly, proportion of the low-stature spruces with abnormalities in crown architecture (dead upper canopies but extensive growth of creeping lowest twigs) increased when approaching the smelter (Kozlov 2001, and unpubl.). The bush-like growth forms were also observed in Scots pine and aspen (*Populus tremula* L.) surviving in industrial barrens near both Monchegorsk and Nikel (Kozlov et al. 1999, unpubl.). Two willow species (*Salix borealis* (Fries.) Nasar. and *S. caprea* L.) in industrial barrens have more epiciormic shoots than in unpolluted forests (Zvereva and Kozlov 2001). The most plausible explanation of all these changes in growth form is the damage of apical (supranival) twigs by wind-driven snow abrasion (Arsenault and Payette 1997), which may be enhanced by pollutants (Alexeyev 1990). Therefore the negative correlations between snow depth and vertical growth of mountain birch, as well as between snow depth and proportion of spruces with abnormal crown architecture, may reflect causal link between these phenomena (Kozlov 2001). An increased light availability (due to forest decline) may also have contributed to higher branching and formation of bush-like crowns in woody plants surviving in barren sites (Zvereva and Kozlov 2001).

6.4 Changes in interactions between organisms

In industrial barrens interactions between organisms may differ from those in unpolluted forests. For example, development of delayed inducible resistance (decrease in plant quality next year after intensive damage), one of the important negative feedbacks regulating population dynamics of herbivores, in boreal willow, *Salix borealis* is disturbed in barren sites (Zvereva and Kozlov 2000b). At the same time, winter and spring bud damage, caused by harsh environmental conditions in barrens, may improve willow quality for herbivores (Zvereva and Kozlov 2000c). These changes in host plant–herbivore interactions favour herbivore outbreaks (see Sect. 4.5). Importantly, compensatory responses of boreal willow to herbivore damage are reduced in industrial barrens (Zvereva and Kozlov 2001), thus damaged plants recover slower than in undisturbed habitats.

Plant–plant interactions, which are mostly competitive in favourable habitats, tend to become positive in stressful environments (Brooker and Callaghan 1998). In industrial barrens, where competition among plants is low due to decreased density, the role of facilitation increases. Near Ventanas smelter in Chile shrubs imposed nursery effect on ground layer vegetation, which lead to better plant recruitment under shrub canopies (Ginocchio et al. 2004). Dwarf shrubs grew and reproduced better under birch canopies compared to between tree gaps in barrens near Monchegosk, whereas in undisturbed habitats the effects of trees were negative (Zvereva and Kozlov 2004). These effects may be explained by alleviation of harsh environmental conditions by trees (Zvereva and Kozlov 2007).

6.5 Adaptation to life in industrial barrens

Heavy metal tolerance of plants has been studied extensively and provides a well-documented example of rapid evolutionary adaptation (Bradshaw and McNeilly 1981; Macnair 1997). Several grass species, including *Agrostis scabra* Willd., *Deschampsia caespitosa* (L.) Beauv., *Agrostis gigantea* Roth. and *Poa compressa* L., colonising Sudbury's metal-contaminated soils, may have developed local metal-tolerant populations (Winterhalder 2000, and references therein). Although pollution tolerance in populations of long-lived trees has been detected less frequently than in populations of grasses and herbs, recently it had been demonstrated that long-lasting pollution impact increased pollution resistance of mountain birch in industrial barrens near both Monchegorsk and Nikel (Kozlov 2005; Eränen 2006), possibly by elimination of sensitive genotypes (survival selection) from the affected populations. Similarly, we discovered that resistance of non-specific esterases (enzymes degrading various xenobiotics) to heavy metals was higher in populations of leaf beetle, *C. lapponica*, from heavily contaminated barren sites (Zvereva et al. 2003). It should be stressed that metal-tolerant populations of plants and animals developed near point polluters represent unique genetic resource that will be lost (overcompeted) with restoration of natural communities following pollution decline.

Some changes in feeding behaviour of herbivorous insects may also be regarded as adaptations to life in the barren landscape. In particular, feeding niche breadth of the leaf beetle, *C. lapponica*, decreased with increase in pollution: in industrial barrens this species concentrated on the boreal willow that assures the best survival of larvae, whereas in surrounding forests it feeds on other willow species as well (Zvereva et al. 1995). Indirect data suggest that in industrial barrens some other herbivores may also prefer other host plants than in undisturbed forests. In particular, larval density of autumnal moth, *Epirrita autumnata* Bkh., measured on birches (most preferred host plant), strongly declined in industrial barrens near Monchegorsk (Ruohomäki et al. 1996). At the same time, the number of moths attracted by pheromone traps did not decline; the moths collected in industrial barrens were metal-contaminated and thus presumably of local origin (pers. obs.). These data suggest that larvae of autumnal moth near Monchegorsk have been feeding on plants other than mountain birch.

7 Significance of industrial barrens

7.1 Industrial barrens as refugia of rare and endangered species and populations

The sites of biological significance within severely degraded environments may not be as rare as is commonly thought, and assumption that physically or chemically hostile environments are incapable of attaining biological diversity is far from being true (Johnson et al. 1978). Industrial barrens are rather heterogeneous (Kozlov 1997; Uhlig et al. 2001; Ginocchio et al. 2004), with a range of different substrate types that favour different species. Therefore, in spite of the general loss of biodiversity, these habitats can develop a great richness of unusual and interesting plants and animals, including regionally rare and endangered species (Johnson et al. 1978; Heliövaara et al. 1990; Eyre and Luff 1995; Spalding and Haes 1995; also see above), and the overall site diversity can be high even when each patch is relatively poor. Furthermore, several plant species of low competitive ability benefit from fragmentation of the continuous ‘carpet’ of vegetation. Invertebrates in industrial barrens may escape from strong enemy pressure, and this ‘enemy-free space’ phenomenon may explain high abundance of some species that are usually depressed in less disturbed habitats (Zvereva and Kozlov 2000a, 2006).

7.2 Conservation of industrial barrens for science, education, and tourism

Although industrial barrens are usually seen as a by-product of human activities that deserves rehabilitation only, and the suggestion to conserve these severely modified landscapes is frequently perceived as a joke, their importance for science, education, and even sightseeing had been sometimes appreciated (Winterhalder 2000). However, conservation of industrial barrens is in line with conservation of historical industrial landscapes which form a part of the World Heritage (UNESCO 2006). Detailed investigation should be conducted prior ‘re-greening’ or rehabilitation of these unusual habitats. Non-selective reclamation works could be destructive to conservation interests, and losses associated with habitat reclamation may easily overcome the benefits gained. In particular, local metal-tolerant populations of plants and animals will definitely be lost.

Prospect of reforestation, that started a more than half of century ago (Seigworth 1943), has created some interest in preserving part of the Copper Basin landscape in its denuded and eroded state for historical purposes (Quinn 1988). Recently, a 200 ha exemplary plot of ‘desert’ remains as part of the display at the Ducktown Museum (Anonymous 2005c). Also a part of Sudbury industrial barrens (about 600 ha surrounding Alice and Baby lakes just behind the abandoned Coniston smelter) is identified in the city reclamation plan as an ‘industrial reserve’. Fortunately or unfortunately, the intention to preserve the extreme level of landscape damage nearly failed: due to natural recovery following pollution decline some 35 years ago the non-reclaimed area is now difficult to distinguish from reclaimed territories (K. Winterhalder and J. Gunn, pers. comm.). Still natural succession on derelict lands may produce unexpected communities of considerable scientific interest (Box 1993). Students and faculty of Laurentian University and other high schools often come to Sudbury to see the 'past and present' of the barren landscape. Industrial barrens at Monchegorsk are frequently visited for 'scientific sightseeing', especially by the researchers from the neighbouring Finland (Ruotsalainen and Markkola 2004); at least once they served a target of an international environmental field course.

As far as we know, only Queenstown had advertised the barren landscapes as tourist attractions. ''By any measure Queenstown is one of the wonders of the world. It is a profound reminder of humanity's capacity to destroy and pollute and, in that sense, it deserves to be seen by everyone'' (Anonymous 2005a). This attitude, supported by local government, prevented reforestation of the hills around Queenstown, although some locals believe that the rainforest, which characterises the area, should be encouraged to regrow. Industrial barrens around Monchegorsk, although neither advertised nor conserved, still attract attention of foreign tourists: quite frequently, buses travelling to/from Murmansk, stop in the barren site for photographing the landscape.

8 Conclusion

8.1 Past and future of industrial barrens

Comparative analysis of the existing data demonstrated that industrial barrens have developed due to combined impact of different stressors, among which soil contamination by heavy metals, clearcutting and fires played the leading role. The combined effects are critical, as either stress alone would have caused much less damage (Jordan 1975). Pollution, accompanied by other human-induced disturbances (primarily clearcutting), damages and gradually kills the vegetation; this process is usually concluded by a fire, facilitated by unusually large amount of woody debris accumulated in severely damaged communities. Since vegetation recovery is hampered by soil toxicity due to extreme contamination by heavy metals, soils remain bare for a long time and suffer from extensive wind and water erosion exacerbated by the intense frost-heaving. The destructive processes are enhanced by both disturbance of negative feedbacks regulating e.g. relationships between plants, herbivores, and their natural enemies, and development of positive feedbacks, e.g. increase in climatic severity due to initial vegetation damage enhances decline of the remaining vegetation.

The most extensive industrial barrens appeared before 1970s; some of them have already been (partially) reclaimed or are recovering following closure of polluters (14 of 36 documented situations; Table 1) or rapid emission decline. Natural recovery of the existing barren sites may take long time; the example of Sudbury suggests that some 20 years after pollution decline may be sufficient to initiate this process. On the other hand, human-assisted recovery may proceed much faster (Vangronsveld et al. 1995, 1996; Winterhalder 2000). However, non-selective reclamation works could be destructive to conservation interests, and the care should be taken to preserve at least some of the unusual post-industrial habitats.

8.2 Industrial barrens as unintentional experiments

Links between pollution-oriented environmental studies ('applied ecology') and development of ecological theories ('basic ecology') are surprisingly weak (Ormerod et al. 1999). Researchers addressing basic ecological problems only rarely use the results of 'unintentional pollution experiments' (Lee 1998). However, industrial barrens offer unique opportunities for conducting 'basic' ecological research, in particular for testing some theories (assumed to be general) in an evolutionary novel stressful environment (Kozlov and Zvereva 2003; Vorobeichik 2004).

Studies in industrial barrens contributed to the development of the theories on plant growth, compensatory ability and reproductive strategies in stressful environment (Zvereva and Kozlov

2001, 2005), as well as to understanding of the role of host plant quality in regulating population dynamics of herbivores in 'enemy free space' (Zvereva et al. 1997). Exploration of plant–plant interactions in industrial barrens demonstrated that shift from competition to facilitation occurs not only in natural stress gradients, that were used to construct the predictive model (Brooker and Callaghan 1998), but also in human-induced stress gradients (Zvereva and Kozlov 2004, 2007). Importantly, results of 'basic' research on plant–plant facilitation are now suggested for practical application in phytostabilisation of heavily contaminated areas (Frérot et al. 2006).

Although net primary production had not been measured in any of industrial barrens, drastic decline in vegetation cover, along with reported retardation in plant growth (e.g. Kryuchkov 1993; Nöjd et al. 1996), suggest that productivity of plant communities declined by a factor of 10–100. Thus, industrial barrens are unique ecosystems capable to maintain relatively high diversity at very low productivity level, and their exploration is likely to contribute to the long-lasting debate (Hector and Schmid 1999; Tilman 1999) on the relationship between diversity, stability and productivity.

8.3 Management of polluted habitats

Recently, most industrial barrens show some signs of natural recovery due to emission decline or closure of responsible polluters; some of them have been or are being successfully revegetated. The latter strategy is in particular justified by the urgent need to prevent dispersion of metals to surrounding areas (e.g. Vandronsveld et al. 1995); it has a strong priority in densely populated sites, like Central Europe, in spite of high scientific and sometimes public interest to unusual post-industrial habitats.

Reclamation strategies used in industrial barrens vary from natural attenuation to extensive (and expensive) revegetation programs. Literature on this problem is rather extensive and had been repeatedly reviewed during the past years (Kozlov et al. 2000b; Winterhalder 2000; Adriano et al. 2004; Kozlov 2004); therefore we provide only a short summary of most relevant findings.

The reduction of emissions is a critical requirement for any reclamation programs. However, until measures to reduce air pollution are fully realised, efforts should be devoted to improving the vitality and maintaining the stability of affected ecosystems. The experience gathered to date suggests that the pollution-induced decline of forests can be slowed down and perhaps even reversed at most stages of degradation. In the case of continuing pollution, its effects can be mitigated to prevent further damage.

Restoration of terrestrial ecosystems after the reduction of emissions is based on the suggestion that some successional stages are not essential and can be bypassed by proper intervention. Thus, in practical terms, the rehabilitation of forests damaged by pollution is an attempt to partially substitute time with money. However, small-scale, short-term experiments still dominate over practical applications. Thus it is reasonably well known how to initiate the early stages of rehabilitation, but there are substantial uncertainties over the longer-term effects (e.g. Eränen and Kozlov 2006). The latter especially concern possible side-effects and ecological risks which may result from human intervention, such as increased leaching of toxic substances and/or nutrients. To reduce these risks, a careful analysis of the need for chemical treatments such as liming or fertilising should be carried out for each specified area. We suggest that whenever possible a 'minimal intervention' approach aimed at promoting natural succession should be used instead of 're-greening' or an artificial re-creation of the desired ecosystem.

Acknowledgements We are grateful to V. Barcan, R. Ginocchio, T. Gorbacheva, J. Gunn, J. Kulfan, P. Niemelä, H. Tømmervik, J. Vangronsveld, E. Vorobeichik, P. Zach, V. Zverev and late K. Winterhalder for providing us with both published and unpublished information. The study was financially supported by the Academy of Finland (project 211734), Maj and Tor Nessling Foundation, and by EC through the BALANCE project carried out under contract EVK2–2002–00169.

References

Acatay A (1968) Damage from injurious gases of Murgul copper plant. Dergisi Istanbul Universitesi Orman Fakultesi 18a(1):1–17

Adriano DC, Wenzel WW, Vangronsveld J, Bolan NS (2004) Role of assisted natural remediation in environmental cleanup. Geoderma 122:121–142

Alexeyev VA (1990) Changes in the growth form of the Scots pine under aerial pollution. In: Tarabrin VP (ed) Industrial botany: the state and perspectives of development. Abstracts of regional scientific conference devoted to the 25th anniversary of Donetsk Botanical Garden, Sept. 1990, Donetsk. Kiev, Ukraine, pp 99–100 (in Russian)

Allum JAE, Dreisinger BR (1987) Remote sensing of vegetation change near Inco's Sudbury mining complexes. Int J Remote Sens 8:399–416

Anand M, Ma KM, Okonski A, Levin S, McCreath D (2003) Characterising biocomplexity and soil microbial dynamics along a smelter-damaged landscape gradient. Sci Tot Environ 311:247–259

Anonymous (1999) Studies of the terrestrial environment in the Wawa Area 1998–1999. http://www.ene.gov.on.ca/envision/techdocs/3918.pdf

Anonymous (2003) Yellowknife EMAN-North Site: Biotic Monitoring & Studies. http://www.emannorth.ca/ic/ds013/settlement.cfm

Anonymous (2005a) Queenstown. http://www.walkabout.com.au/fairfax/locations/TASQueenstown.shtml

Anonymous (2005b) The environmental impact of past mining in the Copper Basin. http://www.gamineral.org/copperbasin.htm

Anononymous (2005c) Ducktown Desert Site. http://ludb.clui.org/ex/i/TN3139

Archibold OW (1978) Vegetation recovery following pollution control at Trail, British Columbia. Can J Bot 56:1625–1637

Arseneault D, Payette S (1997) Landscape change following deforestation at the Arctic tree line in Québec, Canada. Ecology 78:693–706

Badora A, Furrer G, Grünwald A, Schulin R (1998) Immobilization of zinc and cadmium in polluted soils by polynuclear Al_{13} and Al-montmorillonite. J Soil Contamin 7:573–588

Baklanov AA, Rodyushkina IA (1993) Pollution of ambient air by 'Severonikel' smelter complex: observations and modelling. In: Kozlov MV, Haukioja E, Yarmishko VT (eds) Aerial pollution in Kola Peninsula. Proceedings of the international workshop, 14–16 April 1992, St. Petersburg, Russia. Kola Sci. Centre, Apatity, Russia, pp 83–89

Baklanov AA, Sivertsen B (1994) Investigations of local transborder air pollution. NILU F-19/94, Kjeller

Banásová V, Holub Z, Zeleňáková E (1987) The dynamic, structure and heavy metal accumulation in vegetation under long-term influence of Pb and Cu immissions. Ekológia (Bratislava) 6:101–111

Banásová V, Lackovičová A (2004) The disturbance of grasslands in the vicinity of copper plant in the town of Krompachy (Slovenské Rudohorie Mts, NE Slovakia). Bull Slov Bot Spoločn Bratislava 26:153–161

Barcan V (2002) Leaching of nickel and copper from soil contaminated by metallurgical dust. Environ Internat 28:63–68

Barcan VS, Kovnatsky EF (1998) Soil surface geochemical anomaly around the copper–nickel metallurgical smelter. Water Air Soil Pollut 103:197–218

Basta NT, Gradwohl R, Snethen KL, Schroder JL (2001) Chemical immobilization of lead, zinc, and cadmium in smelter-contaminated soils using biosolids and rock phosphate. J Environ Qual 30:1222–1230

Beyer WN, Patee OH, Sileo L, Hoffman DJ, Mulhern BM (1985) Metal contamination in wildlife near two zinc smelters. Environ Pollut 38:63–86

Box J (1993) Conservation or greening? The challenge of post-industrial landscapes. Brit Wildlife 4:273–279

Bradshaw AD, McNeilly T (1981) Evolution and pollution. Edward Arnold, London

Brooker RW, Callaghan TV (1998) The balance between positive and negative plant interactions and its relationship to environmental gradients: a model. Oikos 81:196–207

Buchauer MJ (1973) Contamination of soil and vegetation near a zinc smelter by zink, cadmium, copper, and lead. Environ Sci Technol 7:131–135

Burt R, Wilson MA, Keck TJ, Dougherty BD, Strom DE, Lindhal JA (2003) Trace elements speciation in selected smelter-contaminated soils in Anaconda and Deer Lodge Valley, Montana, USA. Adv Environ Res 8:51–67

Carter DB, Loewenstein H, Pitkin FH (1977) Amelioration and revegetation of smelter-contaminated soils in the Coeur d'Alene mining district of northern Idaho. Paper 13. In: Proceedings of 2nd annual meeting, Canadian Land Reclamation Association, Edmonton, Canada. CLRA, Guelph, Ontario (NV, cited after Winterhalder 2000)

Chernenkova TV (2002) Response of forest vegetation to industrial pollution. Nauka, Moscow (in Russian)

Cicák A, Mihál I, Kulfan J, Šušlík V, Zach P, Krištin A (1999) Health state of forest tree species and selected groups of fungi and animals in surroundings of a magnesium factory (Central Slovakia). Biológia (Bratislava) 18:211–222

Clay G (1983) Copper Basin cover-up. Landscape Architect 94:49–55

Courtin GM (1994) The last 150 years – a history of environmental degradation in Sudbury. Sci Tot Environ 148:99–102

Dawson JL, Nash TH (1980) Effects of air pollution from copper smelters on a desert grassland community. Environ Exptl Bot 20:61–72

Dean RS, Swain RE (1944) Report submitted to the trail smelter arbitral tribunal. US Dept. of the Interior, Bureau of Mines, Bull. 453. US Government Printing Office, Washington

Derome J, Lindroos A-J (1998) Effects of heavy metal contamination on macronutrient availability and acidification parameters in forest soil in the vicinity of the Harjavalta Cu–Ni smelter, SW Finland. Environ Pollut 99:225–232

Derome J, Nieminen T (1998) Metal and macronutrient fluxes in heavy-metal polluted Scots pine ecosystems in SW Finland. Environ Pollut 103:219–228

Disney RHL, Zvereva EL, Mostovsky M (2001) A scuttle fly (Diptera: Phoridae) parasitizing a beetle (Coleoptera: Chrysomelidae) in Russia. Entomol Fenn 12:59–63

Doncheva AV (1978) Landscape in zone of industrial impact. Lesnaya promyshlennost, Moscow

Dudka S, Poncehernandez R, Hutchinson TC (1995) Current level of total element concentrations in the surface layer of Sudbury's soils. Sci Tot Environ 162:161–171

Eastmond RJ (1971) Response of four plant communities to eroded soils and smelter smoke in northern Utah. A Dissertation submitted to the Faculty of the University of Utah. Dept of Biology, Univ. of Utah

Eränen J (2006) Local adaptation of mountain birch to heavy metals in subarctic industrial barrens. Forest Snow Landscape Res 80:161–167

Eränen J, Kozlov MV (2006) Physical sheltering and liming improve survival and performance of mountain birch seedlings: a five-year study in a heavily polluted industrial barren. Restor Ecol 14:77–86

Euler WD (ed) (1939) Effect of sulphur dioxide on vegetation. Nat. Res. Council Canada, Ottawa

Eyre MD, Luff ML (1995) Coleoptera on post-industrial land: a conservation problem? Land Contam Reclam 3:132–134

Filipchuk AN, Kovalev BI (1990) Dynamics of sub-tundra forest decline in Norilsk. In: Anonymous (ed) International Symposium ''Northern forests: state, dynamics human impact'' July 16–26 1990. The USSR State Forest Committee, Moscow, pp 29–37 (in Russian, English summary)

Fowler D, Cape JN, Coyle M, Flechard C, Kuylenstierna J, Hicks K, Derwent D, Johnson C, Stevenson D (1999) The global exposure of forests to air pollutants. Water Air Soil Pollut 116:5–32

Freedman B, Hutchinson TC (1980) Long-term effects of smelter pollution at Sudbury, Ontario, on forest community composition. Can J Bot 58:2123–2140

Frérot H, Lefèbvre C, Gruber W, Collin C, Dos Santos A, Escarré J (2006) Specific interactions between local metallicolous plants improve the phytostabilization of mine soils. Plant Soil 282:53–65

Galbraith H, Lejeune K, Lipton J (1995) Metal and arsenic impacts to soils, vegetation communities and wildlife habitat in southwest Montana uplands contaminated by smelter emissions. 1. Field evaluation. Environ Toxicol Chem 14:1895–1903

Gilbert OL (1975) Effects of air pollution on landscape and land-use around Norwegian aluminium smelters. Environ Pollut 8:113–121

Gilyazov AS (1993) Air pollution impact on the bird communities of the Lapland biosphere reserve. In: Kozlov MV, Haukioja E, Yarmishko VT (eds) Aerial pollution in Kola Peninsula. Proceedings of the international workshop, 14–16 April 1992, St. Petersburg, Russia. Kola Sci. Centre, Apatity, pp 383–390

Ginocchio R (2000) Effects of a copper smelter on a grassland community in the Puchuncavi Valley, Chile. Chemosphere 41:15–23

Ginocchio R, Carvallo G, Toro I, Bustamante E, Silva Y, Sepulveda N (2004) Micro-spatial variation of soil metal pollution and plant recruitment near a copper smelter in Central Chile. Environ Pollut 127:343–352

Goodarzi F, Sanei H, Labonte M, Duncan WF (2002) Sources of lead and zinc associated with metal smelting activities in the Trail area, British Columbia, Canada. J Environ Monitor 4:400–407

Gordon AG, Gorham E (1963) Ecological aspects of air pollution from an iron-sintering plant at Wawa, Ontario. Can J Bot 41:1063–1078

Gorshkov SP (1997) Landscape geoecological mapping of the Norilsk area of ecological disaster. In: Gennadiev AN, Milanova EB (eds) Changes in the environment. Moscow University, Moscow, pp 148–161

Hansen JE, Mitchell JE (1978) The role of terraces and soil amendments in revegetating steep smelter-affected land. Reclam Rev 1:103–112

Haywood JK (1905) Injury to vegetation by smelter fumes. US Dept. of Agriculture, Bureau of Chemistry, Bull. no. 89. Government Printing Office, Washington

Haywood JK (1910) Injury to vegetation and animal life by smelter wastes. US Dept. of Agriculture, Bureau of Chemistry, Bull. no. 113. Government Printing Office, Washington

Hazlett PW, Rutherford GK, vanLoon GW (1983) Metal contaminants in surface soils and vegetation as a result of nickel/copper smelting at Coniston, Ontario, Canada. Reclam Reveg Res 2:123–137

Hector A, Schmid B (1999) Plant diversity and productivity experiments in European grasslands. Science 286:1123–1127

Hedgcock GG (1912) Winter-killing and smelter-injury in the forests of Montana. Torreya 12:25–30

Heliövaara K, Väisänen R, Mannerkoski I (1990) *Melanophila formaneki* (Jakobson) (Coleoptera, Buprestidae) new to Finland. Ent Fenn 1:221–225

Helmisaari H-S, Derome J, Fritze H, Nieminen T, Palmgren K, Salemaa M, Vanha-Majamaa I (1995) Copper in Scots pine forests around a heavy-metal smelter in south western Finland. Water Air Soil Pollut 85:1727–1732

Henderson PJ, McMartin I, Hall GE, Persival JB, Walker DA (1998) The chemical and physical characteristics of heavy metals in humus and till in the vicinity of the base metal smelter at Flin Flon, Manitoba, Canada. Environ Geol 34:39–58

Hepting GH (1971) Air pollution and trees. In: Matthews WH, Smith FE, Goldberg ED (eds) Man's impact on terrestrial and oceanic ecosystems. MIT Press, Cambridge Mass, pp 116–197

Hocking D, Kuchar P, Plambeck JA, Smith RA (1978) Impact of gold smelter emissions on vegetation and soils of a sub-arctic forest-tundra transition ecosystem. J Air Pollut Control Assoc 28:133–137

Hodgson DA, Vyverman W, Chepstow-Lusty A, Tyler PA (2000) From rainforest to wasteland in 100 years: the limnological legacy of the Queenstown mines, Western Tasmania. Archiv Hydrobiol 149:153–176

Hogan GD, Wotton DL (1984) Pollutant distribution and effects in forests adjacent to smelters. J Environ Qual 13:377–382

Hursh CR (1948) Local climate in Copper Basin of Tennessee as modified by the removal of vegetation. USDA Circ. no. 774. USDA, Washington

Hutchinson TC, Whitbey LM (1974) Heavy metal pollution in the Sudbury mining and smelting region of Canada. I. Soil and vegetation contamination by nickel copper and other metals. Environ Conserv 1:123–132

Hutchinson TC, Symington MS (1997) Persistence of metal stress in a forested ecosystem near Sudbury, 66 years after closure of the O'Donnell roast bed. J Geochem Explor 58:323–330

Hutchinson TC, Aufreiter S, Hancock RGV (1982) Arsenic pollution in the Yellowknife area from gold smelter activities. J Radioanalyt Chem 71:59–73

Igamberdiev VM, Tereshenkov OM, Kutyev HA, Popova EN (1994) Evaluation of the recent state of the environment in the Norilsk industrial area. Econ Komi Repub 3:54–61 (in Russian)

James GI, Courtin GM (1985) Stand structure and growth form of the birch transition community in an industrially damaged ecosystem, Sudbury, Ontario. Can J Forest Res 15:809–817

Johnson D, Hale B (2004) White birch (*Betula papyrifera* Marshall) foliar litter decomposition in relation to trace metal atmospheric inputs at metal-contaminated and uncontaminated sites near Sudbury, Ontario and Rouyn-Noranda, Quebec, Canada. Environ Pollut 127:65–72

Johnson MS, Putwain PD, Holliday RJ (1978) Wildlife conservation value of derelict metalliferous mine workings in Wales. Biol Conserv 14:131–148

Jordan MJ (1975) Effects of zinc smelter emissions and fire on a chestnut-oak woodland. Ecology 56:78–91

Kapusta M & Múdry P (1974) Long-run effect of immissions from smelting works in Banská Štiavnica on vegetation and landscape. Acta Geobot III(8):85–126

Kautz G, Zimmer M, Zach P, Kulfan J, Topp W (2001) Suppression of soil microorganisms by emissions of a magnesite plant in the Slovak Republic. Water Air Soil Pollut 125:121–132

Kelly JJ, Tate RL (1998) Effects of heavy metal contamination and remediation on soil microbial communities in the vicinity of a zinc smelter. J Environ Qual 27:609–617

Kharuk VI (2000) Air pollution impacts on subarctic forests at Noril'sk, Siberia. In: Innes JL, Oleksyn J (eds) Forest dynamics in heavily polluted regions. (IUFRO task force on environmental change. Report no. 1). CAB International, Wallingford, pp 77–86

Kharuk VI, Winterberger K, Tsibulskii GM, Yakhimovich AP, Moroz SN (1996) Technogenic disturbance of sub-tundra forests in the Norilsk valley. Ekologia (Ekaterinburg) 27:406–410 (in Russian)

Kleinert J (1988) Synusiae of ground beetles (Coleoptera: Carabidae) in the environs of Ješlava and Lubenik affected by alkaline emissions. Biológia (Bratislava) 43:159–167

Komulainen M, Vieno M, Yarmishko VT, Daletskaja TD, Maznaja EA (1994) Seedling establishment from seeds and seed banks in forests under long-term pollution stress – a potential for vegetation recovery. Can J Bot 72:143–149

Koponen S, Niemelä P (1993) Ground-living spiders in a polluted pine forest SW Finland. Boll Acc Gioenia Sci Nat 26:221–226

Koponen S, Niemelä P (1995) Ground-living arthropods along pollution gradient in boreal pine forest. Ent Fenn 6:127–131

Kozlov MV (1997) Pollution impact on insect biodiversity in boreal forests: evaluation of effects and perspectives of recovery. In: Crawford RMM (ed) Disturbance and recovery in arctic lands: an ecological perspective. Proceedings of the NATO advanced research workshop on disturbance and recovery of arctic terrestrial ecosystems, Rovaniemi, Finland, 24–30 September 1995 (NATO ASI series. Partnership subseries 2. Environment, vol 25). Kluwer Academic Publishers, Dordrecht, pp 213–250

Kozlov MV (2001) Snowpack changes around a nickel–copper smelter at Monchegorsk northwestern Russia. Can J Forest Res 31:1684–1690

Kozlov MV (2002) Changes in wind regime around a nickel–copper smelter at Monchegorsk northwestern Russia. Int J Biometeorol 46:76–80

Kozlov MV (2003) Density fluctuations of the leafminer *Phyllonorycter strigulatella* (Lepidoptera: Gracillariidae) in the impact zone of a power plant. Environ Pollut 121: 1–10

Kozlov MV (2004) Silviculture in polluted areas. In: Burley J, Evans J, Youngquist JA (eds) Encyclopedia of forest science. Elsevier Academic Press, London, pp 1112–1121

Kozlov MV (2005) Pollution resistance of mountain birch, *Betula pubescens* subsp. *czerepanovii* near the copper–nickel smelter: natural selection or phenotypic acclimation? Chemosphere 59:189–197

Kozlov MV, Haukioja E (1995) Pollution-related environmental gradients around the ''Severonickel'' smelter complex on Kola Peninsula, Northwestern Russia. In: Munawar M, Luotola M (eds) The contaminants in the Nordic Ecosystem: Dynamics, processes and fate. S.P.B. Academic Publ., The Netherlands, pp 59–69

Kozlov MV, Haukioja E (1997) Microclimate changes along a strong pollution gradient in northern boreal forest zone. In: Uso JL, Brebbia CA, Power H (eds) Ecosystems and sustainable development (Advances in Ecological Sciences vol 1). Computation Mechanics Publ, Southampton, pp 603–614

Kozlov MV, Haukioja E (1999) Performance of birch seedlings replanted in heavily polluted industrial barrens of the Kola Peninsula NW Russia. Restor Ecol 7:145–154

Kozlov MV, Zvereva EL (2003) Impact of industrial polluters on terrestrial ecosystems: a research synthesis. In: Honkanen JO Koponen PS (eds) Sixth Finnish conference of environmental sciences: Proceedings. Finnish Society for Environmental Sciences & University of Joensuu, Joensuu, Finland, pp 72–75

Kozlov MV, Zvereva EL (2004) Reproduction of mountain birch along a strong pollution gradient near Monchegorsk, Northwestern Russia. Environ Pollut 132:443–451

Kozlov MV, Jalava J, Lvovsky AL, Mikkola K (1996) Population densities and diversity of Noctuidae (Lepidoptera) along an air pollution gradient on the Kola Peninsula, Russia. Entomol Fenn 7:9–15

Kozlov MV, Byalt VV, Salo J (1998) Species richness of vascular plants in studies of human-induced disturbances in northern coniferous forests: effect of scale. In: Gorshkov VG, Makarieva AM, Kharkina TG (eds) The role of virgin terrestrial biota in the modern processes of global change: biotic regulation of the environment. Proceedings of international seminar, 12–16 October 1998, Petrozavodsk. St. Petersburg Institute of Nuclear Physics, Gatchina, Russia, pp 305–307

Kozlov MV, Zvereva EL, Niemelä P (1999) Effects of soil quality and air pollution on the rooting and survival of *Salix borealis* cuttings. Boreal Environ Res 4:67–76

Kozlov MV, Haukioja E, Bakhtiarov AV, Stroganov DN, Zimina SN (2000a) Root *vs* canopy uptake of heavy metals by birch in an industrially polluted area: contrasting behaviour of nickel and copper. Environ Pollut 107:413–420

Kozlov MV, Haukioja E, Niemelä P, Zvereva E, Kytö M (2000b) Revitalization and restoration of boreal and temperate forests damaged by aerial pollution. In: Innes JL, Oleksyn J (eds) Forest dynamics in heavily polluted regions (IUFRO task force on environmental change. Report no. 1). CAB International, Wellingford, pp 193–218

Kozlov MV, Zvereva EL, Niemelä P (2001) Shoot fluctuating asymmetry: a new and objective stress index in Norway spruce (Picea abies). Can J Forest Res 31:1289–1291

Kozlov MV, Brodskaya NK, Haarto A, Kuusela K, Schäfer M, Zverev V (2005a) Population densities and diversity of blood-sucking flies (Diptera: Ceratopogonidae, Culicidae, Tabanidae, Simuliidae) around a nickel–copper smelter at Monchegorsk, Northwestern Russia. J Vector Ecol 30:263–271

Kozlov MV, Zvereva EL, Gilyazov AS, Kataev GD (2005b) Contaminated zone around a nickel-copper smelter: a death trap for birds and mammals? In: Burk AR (ed) Trends in biodiversity research. Nova Science Publishers, New York, pp 81–99

Kryuchkov VV (1993) Extreme anthropogenic loads and the northern ecosystem condition. Ecol Appl 3:622–630

Kryuchkov VV, Makarova TA (1989) Impact of industrial air pollution on ecosystems of the Kola North. Kola Sci. Centre, Apatity (in Russian)

Kulagin YZ (1964) Smoke wastes of ‘Magnezit’ plant and dynamics of green belt forests around the city of Satka (Southern Ural). In: Mamaev SA (ed) Vegetation and industrial pollution (materials of conference). Ural State University, Sverdlovsk, pp 175–187 (in Russian)

Lee JA (1998) Unintentional experiments with terrestrial ecosystems: ecological effects of sulphur and nitrogen pollutants. J Ecol 86:1–12

Lees D (2000) Green rebirth. Can Geogr 120:61–71

Lehmann C, Rebele F (2004) Evaluation of heavy metal tolerance in *Calamagrostis epigejos* and *Elymus repens* revealed copper tolerance in a copper smelter population of *C. epigejos*. Environ Exptl Bot 51:199–213

Linzon SN (1975) Forest ecosystems: the effects of atmospheric sulfur. In: Klein WM, Severson JG (eds) Sulphur in the environment. Missouri Botanical Garden St. Louis, Missouri, pp 112–133

Lukina NV, Nikonov VV (1996) Biogeochemical cycles in the northern forests subjected to air pollution. Institute of North Industrial Ecology Problems, Apatity (in Russian)

Lukina NV, Nikonov VV (1999) Pollution-induced changes in soils subjected to intense air pollution. In: Nikonov VV, Koptsik GN (eds) Acidic deposition and forest soils. Kola Science Centre, Apatity, Russia, pp 79–126 (in Russian)

Lurie NY (1986) Impact of industrial pollution on structure and function of microbial coenoses in the black earth of Southern Ural. PhD. VV Dokuchaev Soil Institute, Moscow (in Russian)

MacMillan D (2000) Smoke wars: Anaconda copper, Montana air pollution and the courts 1890–1924. Montana Historical Society Press, Montana

Macnair MR (1997) The evolution of plants in metal-contaminated environments. In: Bijlsma R, Loeschchke V (eds) Environmental stress adaptation and evolution . Birkhäuser Verlag Basel, Switzerland, pp 3–24

Makhnev AK, Trubina MR, Pryamonosova SA (1990) Forest vegetation in surroundings of non-ferrous plants. In: Shiyatov SG, Shilova A (eds) Natural vegetation of industrial and urban areas of Ural. Ural Division of the Academy of Science of the USSR, Sverdlovsk, Russia, pp 3–40 (in Russian)

Makunina GS (2002) Degradation and chemical properties of soils in the industrially altered area of Karabash. Pochvovedenie [Soil Science, Moscow] 0(3): 368–376 (in Russian, English summary)

Mälkönen E, Derome J, Fritze H, Helmisaari H-S, Kukkola M, Kytö M, Saarsalmi A, Salemaa M (1999) Compensatory fertilization of Scots pine stands polluted by heavy metals. Nutr Cycl Agroecosyst 55:239–268

Maňňkovská B (1984) The effects of atmospheric emissions from the Krompachy, Nižná Slaná, Rudňany iron ore mines on forest vegetation and soils. Ekológia (Bratislava) 3:331–344

Manninen S, Huttunen S (1997) Critical level of SO_2 for subarctic Scots pine forests. In: Anonymous (ed) The AMAP international symposium on environmental pollution in the Arctic. 1–5 June 1997. Extended Abstracts. Tromsø, Norway, pp 173–174

Marin YuF (1996) On the impact of Kirovgrad copper smelter on the environment. In: Marin YuF (ed) Problems of reserve management. 25th anniversary of Visim reserve: materials of the scientific conference.

Ekaterinburg Publishers, Ekaterinburg, Russia, pp 87–91 (in Russian)

Marty L (2000) The use of local ecotypes for the revegetation of acid/heavy metal contaminated lands in western Montana. In: Billings land reclamation symposium 2000: striving for restoration, fostering technology and policy for reestablishing ecological function, March 20–24, 2000, Billings, Montana, pp 216–228. http://www.ott.wrcc.osmre.gov/library/proceed/recsym.htm

McCall J, Gunn J, Struik H (1995) Photo interpretive study of recovery of damaged lands near the metal smelters of Sudbury, Canada. Water Air Soil Pollut 85:847–852

McEnroe NA, Helmisaari H-S (2001) Decomposition of coniferous forest litter along a heavy metal pollution gradient south-west Finland. Environ Pollut 113:11–18

McGovern PC (1975) Effects of sulphur dioxide and heavy metals on the Wawa area soils and vegetation (1974). Ontario Minist. Environ., Northeast Region, Sudbury

Menshchikov SL, Vlasenko VE, Estyugin AS (1997) Local monitoring of forest ecosystems under variable types of pollution. In: Makhnev AK (ed) Biological recultivation of disturbed lands. Proceedings of the international congress, 26–29 August 1996. Institute of Forest, Ekaterinburg, pp 184–192 (in Russian)

Mitchell J (1982) Revegetation of lands surrounding the Bell Bay smelter. In: Murray F (ed) Fluoride emissions: their monitoring and effects on vegetation and ecosystems. Academic Press, Sydney, pp 207–215

Nielsen D, Kovats Z (2004) Report on analysis of the effects of smelter emissions on vegetation within Trail regional area. http://www.teckcominco.com/articles/tr-ecorisk/techreports/2004/2004–05-veganalysis.pdf

Nieminen TM (2004) Effects of soil copper and nickel on survival and growth of Scots pine. J Environ Monitoring 6:888–896

Nieminen TM, Ukonmaanaho L, Shotyk W (2002) Enrichment of Cu, Ni, Zn, Pb and As in an ombrotrophic peat bog near a Cu-Ni smelter in southwest Finland. Sci Tot Environ 292:81–89

Niskavaara H, Reimann C, Chekushin V (1996) Distribution and pathways of heavy metals and sulphur in the vicinity of the copper-nickel smelters in Nikel and Zapoljarnij, Kola Peninsula, Russia as revealed by different sample media. Appl Geochem 11:25–34

Nöjd P, Mikkola K & Saranpää P (1996) History of forest damage in Monchegorsk, Kola: a retrospective analysis based on tree rings. Can J Forest Res 26:1805–1812

Nriagu JO, Wong HKT, Lawson G, Daniel P (1998) Saturation of ecosystems with toxic metals in Sudbury basin, Ontario, Canada. Sci Tot Environ 223:99–117

Ormerod SJ, Pienkowski MW, Watkinson AR (1999) Communicating the value of ecology. J Appl Ecol 36:847–855

Padgett PE, Kee SN (2004) Impacts of air pollution on forest ecosystems. In: Burley J, Evans J, Youngquist JA (eds) Encyclopedia of forest science. Elsevier Academic Press, London, pp 132–139

Pancholy SK, Rice EL, Turner JA (1975) Soil factors preventing revegetation of a denuded area near an abandoned zinc smelter in Oklahoma. J Appl Ecol 12:337–342

Pearce F (1994) Europe top 100 polluters. New Scientist 143:9

Pommerening E (1977) Revegetation of Coeur-d'Alene mining district. Mining Congress J 63:20–23

Quinn M-L (1988) Tennessee's Copper Basin: A case for preserving an abused landscape. J Soil Water Conserv 43:140–144

Quinn M-L (1989) Early smelter sites: a neglected chapter in the history and geography of acid rain in the United States. Atmos Environ 23:1281–1292

Ragaini RC, Ralston HR, Roberts N (1977) Environmental trace-metal contamination in Kellogg, Idaho, near a lead smelting complex. Environ Sci Technol 11:773–781

Rassi P, Alanen A, Kemppainen E, Vickholm M, Väisänen R (eds) (1985) Uhanalaisten Eläinten ja Kasvien Suojelutoimikunnan Mietintö. II. Suomen Uhanalaiset Eläimet. Komiteanmietintö 43, Ympäristöministeriö, Helsinki (in Finnish)

Ratkin NE (1999) Application of the calculation method for estimating the pollutants accumulation in snow cover. In: Kalabin GV (ed) Ecological and geographical problems of the Kola North. Institute of North Industrial Ecology Problems, Apatity, pp 42–54 (in Russian)

Rebele F, Surma A, Kuznik C, Bornkamm R, Brej T (1993) Heavymetal contamination of spontaneous vegetation and soil around the copper smelter Legnica. Acta Soc Bot Pol 62:53–57

Redente EF, Zadeh H, Paschke MW (2002) Phytoxicity of smelter-impacted soils in southwest Montana, USA. Environ Toxicol Chem 21:269–274

Redente EF, Richards JL (1997) Effects of lime and fertilizer amendments on plant growth in smelter impacted sols in Montana. Arid Soil Res Rehabil 11:353–366

Reimann C, de Caritat P, Niskavaara H, Finne TE, Kashulina G, Pavlov VA (1998) Comparison of elemental contents in O- and C-horizon soils from the surroundings of Nikel, Kola Peninsula, using different grain size fractions and extractions. Geoderma 84:65–87

Rigina O, Kozlov MV (2000) Pollution impact on sub-Arctic northern taiga forests in the Kola peninsula Russia. In: Innes JL, Oleksyn J (eds) Forest dynamics in heavily polluted regions (IUFRO task force on environmental change. Report no. 1). CAB International, Wallingford, pp 37–65

Richter VA, Zvereva EL (1996) The tachinid species *Cleonice nitidiuscula* Zetterstedt new for fauna of Murmansk Province (Diptera: Tachinidae). Zoosyst Ross 6:202

Ruohomäki K, Kaitaniemi P, Kozlov MV, Tammaru T, Haukioja E, (1996) Density and performance of *Epirrita autumnata* (Lep., Geometridae) along three air pollution gradients in northern Europe. J Appl Ecol 33:773–785

Ruotsalainen AL, Markkola AM (2004) Kuolan niemimaalla kesällä 2003 pieni matkakertomus. Luonnon Tutkija 4:135–143

Rybicka EH, Jędrzejczyk B (1995) Preliminary studies on mobilization of copper and lead from contaminated soils and readsorption on competing sorbents. Appl Clay Sci 10:259–268

Sahi VM (1983) Frost heaving and needle ice formation and their effect upon seedling survival at selected sites in Sudbury. [MSc]. Laurentian University, Ontario

Salemaa M, Vanha-Majamaa I, Derome J (2001) Understorey vegetation along a heavy-metal pollution gradient in SW Finland. Environ Pollut 112:339–350

Šály R, Mihálik A (1985) Influence of magnesite plant immissions on mineral composition of soils. In: Klimo E, Šály R (eds) Air pollution and stability of coniferous forest ecosystems: international symposium. October 1–5, 1984. Institute of Forest Ecology, Brno, Czechoslovakia. University of Agriculture, Brno, pp 99–112

Savchenko VA (1998) Ecological problems of Taymyr. Russian Academy of Engineers, Moscow (in Russian)

Seigworth KL (1943) Ducktown – a postwar challenge. Am Forestry 49:521–523

Shilova II, Lukjanets AI (1989) Successions of steppe vegetation on areas impacted by aerial industrial emissions of non-ferrous metallurgy. In: Makhnev AK, Shilova II (eds) Vegetation of industrial landscapes of Ural. Institute of Plant and Animal Ecology, Sverdlovsk, pp 56–79 (in Russian)

Shilova II, Makhnev AK, Lukjanets AI (1984) Geochemical transformation of soils and vegetation on territories adjacent to non-ferrous metallurgy enterprises. In: Mamaev SA, Shilova II (eds) Ecological aspects of optimisation of industrial landscapes. Institute of Plant and Animal Ecology, Sverdlovsk, pp 14–35 (in Russian)

Shoji K, Sugai M (1992) The Ashio copper mine pollution case: the origins of environmental destruction. In: Ui J (ed) Industrial pollution in Japan. United Nations University Press, Tokyo, pp 18–63

Sivertsen B, Baklanov A, Hagen L, Makarova T (1994) Air pollution in the border areas of Norway and Russia. Summary report 1991–1993. NILU OR 56/94, Kjeller

Sokolov GI (1996) Forest decline near the city of Satka, Chelyabinsk region, due to industrial emissions of 'Magnesit' plant. In: Mozolevskaya EG, Sharapa TV (eds) International scientific conference 'Impact of atmospheric pollution and other human-created and natural factors on destabilization of forests in Central and Eastern Europe'. Abstracts of presentations, vol 1. Moscow State Forest University, Moscow, pp 35–37 (in Russian)

Sopper WE (1989) Revegetation of a contaminated zinc smelter site. Landscape Urban Plan 17:241–250

Spalding A, Haes ECM (1995) Contaminated land – a resource of wildlife: a review and survey of insects on metalliferous mine sites in Cornwall. Land Contam Reclam 3:24–29

Stavrova NI (1990) Regeneration of Scots Pine (*Pinus sylvestris* L.) in Northern Taiga forests under the impact of industrial pollution [PhD]. Komarov Botanical Institute, Leningrad, Russia (in Russian)

Stepanov AM, Chernenkova TV (1989) A study of forest biocenoses in the vicinity of copper plant. Izvestiya Akad Nauk Ser Biol 0(3):356–363 (in Russian)

Suding KN, Gross KL, Houseman GR (2004) Alternative states and positive feedbacks in restoration ecology. Trends Ecol Evol 9:46–53

Sutinen ML, Raitio H, Nivala V, Ollikainen R, Ritari A (1996) Effects of emissions from copper-nickel smelters on the frost hardiness of *Pinus sylvestris* needles in the subarctic region. New Phytol 132:503–512

Swain RE, Harkins WD (1908) Papers on smelter smoke. Arsenic in vegetation exposed to smelter smoke. J Am Chem Soc 30:915–928

Tarko AM, Bykadorov AV, Kryuchkov VV (1995) Modeling of air-pollution impacts on regional forest ecosystems. Doklady Rus Acad Sci 341:571–573 (in Russian)

Teale EW (1951) The murder of a landscape. Nat Hist 60:352–356

Tilman D (1999) The ecological consequences of changes in biodiversity: a search for general principles. Ecology 80:1455–1474

Tømmervik H, Hogda KA, Solheim L (2003) Monitoring vegetation changes in Pasvik (Norway) and Pechenga in Kola Peninsula (Russia) using multitemporal Landsat MSS/TM data. Rem Sens Environ 85:370–388

Tsvetkov VF (1991) State of forests subjected to industrial emission impact in Murmansk region and problems of their preservation. In: Anonymous (ed) Ecological research in forests of the European North. Arkhangelsk Institute of Forestry and Forest Chemistry, Arkhangelsk, pp 125–136 (in Russian)

Tucekova A (2001) Doriesenie umelej obnovy tazko zalesnitelnych ploch v magnezitovej imisnej oblasti Jelsava – Lubenik. [Artificial regeneration of scarcely reforestable area in a polluted area Jelsava – Lubenik]. Štúdia LVÚ, Zvolen (in Slovak)

Uhlig C, Salemaa M, Vanha-Majamaa I, Derome J (2001) Element distribution in *Empetrum nigrum* microsites at heavy metal contaminated sites in Harjavalta, western Finland. Environ Pollut 112:435–442

UNESCO (2006) World Heritage. http://whc.unesco.org/en

Usui H, Suzuki H (1973) Ecological and revegetational problems of the Ashio devastated area. In: Hutnik RJ, Davis G (eds) Ecology and reclamation of devastated land, vol 2. Gordon & Breach, NY, pp 395–406

Väisänen S (1986) Effects of air pollution by metal, chemical and fertilizer plants on forest vegetation at Kokkola, W Finland. Ann Bot Fenn 23:305–315

Vajda A, Venalainen A (2005) Feedback processes between climate, surface and vegetation at the northern climatological tree-line (Finnish Lapland). Boreal Environ Res 10:299–314

Vangronsveld J, Colpaert JV, VanTichelen KK (1996) Reclamation of a bare industrial area contaminated by non-ferrous metals: physico-chemical and biological evaluation of the durability of soil treatment and revegetation. Environ Pollut 94:131–140

Vangronsveld J, Vanassche F, Clijsters H (1995) Reclamation of a bare industrial-area contaminated by nonferrous metals: *in situ* metal immobilization and revegetation. Environ Pollut 87(1):51–59

Vorobeichik EL (2003) Ecological standartization of the toxicity loads on terrestrial ecosystems. [Doct]. Instutute of Plant and Animal Ecology of Ural division of Russian Academy of Scienses, Ekaterinburg (in Russian)

Vorobeichik EL (2004) Ecology of the impacted regions: prospects for basic research. In: Zhuikova TV (ed) Materials of the 6th meetings on populations. State Social and Pedagogical Academy, Nizhnij Tagil, pp 36–45

Vorobeichik EL, Marin YuF, Zhigalskii OA, Goryachev VM, Hantemirova EV, Lukjanov OA, Mikhailova IN, Kaigorodova SYu, Goldberg IL (1996) Prospects of the use of Visim reserve for studies of human impacts on terrestrial ecosystems. In: Marin YuF (ed) Problems of natural reserves. 25th anniversary of the Vitim reserve. Ekaterinburg Publ. House, Ekaterinburg, pp 19–23 (in Russian)

Vlasova TM, Filipchuk AN (1990) Selection of bioindicators for local monitoring of northern forests under aerial industrial pressure. In: Anonymous (ed) International symposium ‘‘Northern forests: state, dynamics, human impact’’, July 16–26, 1990. The USSR State Forest Committee, Moscow, pp 6–17 (in Russian, English summary)

Weber J (2002) Scanning electron microscope approaches to heavy metal polluted soils in the vicinity of the copper smelter. In: International conference on sustainable land use and management 2002, Çanakkale. www.toprak.org.tr/isd/can_52.htm

Wilcke W, Guschker C, Kobza J, Zech W (1999) Heavy metal concentrations, partitioning, and storage in Slovak forest and arable soils along a deposition gradient. J Plant Nutrition Soil Sci 162:223–229

Winterhalder K (2002) Reclamation of smelter-damaged lands. In: Richard I, Barnhisel RI, Darmody RG, Daniels WL (eds) Reclamation of drastically disturbed lands (Agronomy Monograph, no. 41). American Society of Agronomy, Madison, pp 819–853

Winterhalder K, Lautenbach WE, Beckett P (2001) The Sudbury regional land reclamation program: a case study. In: Burley JB (ed) Environmental design for reclaiming surface mines. The Edwin Mellen Press, Lewinston, pp 286–294

Winterhalder K (2003) Minimal Amelioration as appropriate technology in the Green Flin Flon/Creighton. Paper presented at Sudbury 2003 Mining and the Environment, Laurentian University, Sudbury, Ontario, May 25–28, 2003 http://www.ott.wrcc.osmre.gov/library/proceed/sudbury2003/sudbury03/173.pdf

Wolak J (1970) Formation of new ecological systems under the impact of industrial emissions. Sylwan 114(9):35–39 (in Polish)

Wołk A (1977) Microclimate alterations in relation to the extent of forest destruction in vicinity of the nitrogen plant at Puławy. Sylwan 121(7):33–46 (in Polish)

Wolt DJ, Lietzke DA (1982) The influence of anthropogenic sulfur inputs upon soil properties in the Copper Basin region of Tennessee. Soil Sci Soc Am J 46:651–656

Wood CW, Nash TN III (1976) Copper smelter effluent effects on Sonoran desert vegetation. Ecology 57:1311–1316

Zeid IM (2001) Responses of *Phaseolus vulgaris* to chromium and cobalt treatments. Biol Plant 44:111–115

Zvereva EL, Kozlov MV (2000a) Effect of air pollution on natural enemies of the leaf beetle, *Melasoma lapponica*. J Appl Ecol 37:298–308

Zvereva EL, Kozlov MV (2000b) Pollution suppresses delayed inducible resistance in boreal willow *Salix borealis*. Ecol Lett 3:85–89

Zvereva EL, Kozlov MV (2000c) Bud removal alleviates negative effects of pollution on quality of *Salix borealis* for insect herbivore. Basic Appl Ecol 1:171–176

Zvereva EL, Kozlov MV (2001) Effects of pollution induced habitat disturbance on the response of willows to simulated herbivory. J Ecol 89:21–30

Zvereva EL, Kozlov MV (2004) Facilitative effects of top-canopy plants on four dwarf shrub species in habitats severely disturbed by pollution. J Ecol 92:288–296

Zvereva EL, Kozlov MV (2005) Growth and reproduction of dwarf shrubs, *Vaccinium myrtillus* and *V. vitis-idaea*, in a severely polluted area. Basic Appl Ecol 6:261–274

Zvereva EL, Kozlov MV (2006) Top-down effects on population dynamics of *Eriocrania* miners (Lepidoptera) under pollution impact: does enemy-free space exist? Oikos 115:413–426

Zvereva EL, Kozlov MV (2007) Facilitation of bilberry by mountain birch in habitat severely disturbed by pollution: importance of sheltering. Environ. Exptl. Bot. doi:10.1016/j.envexpbot.2006.10.005

Zvereva EL, Kozlov MV, Neuvonen S (1995) Decrease in feeding niche breadth of *Melasoma lapponica* (Coleoptera: Chrysomelidae) with increase in pollution. Oecologia 104:323–329

Zvereva EL, Kozlov MV, Niemelä P, Haukioja E (1997) Delayed induced resistance and increase in leaf fluctuating asymmetry as responses of *Salix borealis* to insect herbivory. Oecologia 102:368–373

Zvereva EL, Kozlov MV, Kruglova OYu (2002) Color polymorphism in relation to population dynamics of the leaf beetle *Chrysomela lapponica*. Evol Ecol 16:523–539

Zvereva EL, Serebrov V, Glupov V, Dubovsky I (2003) Activity and heavy metal resistance of non-specific esterases in leaf beetle *Chrysomela lapponica* from polluted and unpolluted habitats. Comp Biochem Physiol (Part C) 135:383–391