Chapter 2
Methodology of the Research and Description of Polluters

2.1 Selection of Polluters

In order to obtain an unbiased estimate of the overall effect of point polluters on terrestrial biota, we needed to explore a random sample from the entire population of polluters. Unfortunately, this task is hardly feasible, keeping in mind obvious financial and time constraints. Therefore we selected a representative sample of point polluters according to the following basic criteria:

1. The explored polluters should represent the entire range of pollution loads, from highest to reasonably low.
2. Basic types of polluters (identified in earlier meta-analyses; Ruotsalainen & Kozlov 2006; Zvereva et al. 2008) should be included.
3. Impact zones should represent the basic vegetation types of the northern and temperate regions of the Northern hemisphere.

When other selection criteria were met, the preference was given to impact zones that were best studied either by our team or by other researchers.

We explored environmental effects imposed by 18 point polluters (Fig. 2.1; Table 2.1) representing five of six classes that were used in earlier meta-analyses (Ruotsalainen & Kozlov 2006; Zvereva et al. 2008): non-ferrous industries, emitting heavy metals and SO_2; aluminium plants, emitting fluorine; iron and steel producing factories, emitting both SO_2 and alkaline dust; fertilising and chemical plants, emitting various nitrogen and sulphur containing compounds; and power stations, emitting mostly SO_2. Detailed information on these polluters is given below (Section 2.2). Table 2.1 shows classifications of these polluters, listing the variables that are used in categorical meta-analysis (Section 2.5).

M.V. Kozlov et al. *Impacts of Point Polluters on Terrestrial Biota*,
DOI 10.1007/978-90-481-2467-1_2,

Fig. 2.1 Location of the investigated polluters

Table 2.1 Values of classificatory variables used in meta-analysis

Locality and polluter	Classificatory variables		
	Polluter type[a]	Effect on soil pH[b]	Geographic position[c]
Apatity, Russia: power plant	Pow	B	N
Bratsk, Russia: aluminium smelter	Al	B	S
Harjavalta, Finland: nickel-copper smelter	Nf	N	S
Jonava, Lithuania: fertiliser factory	Fert	N	S
Kandalaksha, Russia: aluminium smelter	Al	B	N
Karabash, Russia: copper smelter	Nf	A	S
Kostomuksha, Russia: iron pellet plant	Fe	B	S
Krompachy, Slovakia: copper smelter	Nf	A	S
Monchegorsk, Russia: nickel-copper smelter	Nf	A	N
Nadvoitsy, Russia: aluminium smelter	Al	B	N
Nikel, Russia: nickel-copper smelter	Nf	A	N
Norilsk, Russia: nickel-copper smelters	Nf	N	N
Revda, Russia: copper smelter	Nf	A	S
Straumsvík, Iceland: aluminium smelter	Al	N	N
Sudbury, Canada: nickel-copper smelter	Nf	N	S
Volkhov, Russia: aluminium smelter	Al	B	S
Vorkuta, Russia: power plant	Pow	B	N
Žiar nad Hronom, Slovakia: aluminium smelter	Al	B	S

[a] Classification follows Zvereva et al. (2008).

[b] A, acidifying; B, alkalysing; N, neutral; classification is primarily based on data reported in Section 3.3.

[c] Classification is based on mean July temperature: below 14°C – northern polluters (N); above 14°C – southern polluters (S). For a map showing location of polluters, consult Fig. 2.1; coordinates of polluters are given in Tables 2.25–2.42; climatic data are summarised in Table 2.2.

2.2 History of the Selected Polluters and Their Environmental Impacts

2.2.1 Introduction

In this chapter, we provide background information on both polluters selected for our study and their environmental impacts. We also briefly describe the surrounding landscapes (climatic data are summarised in Table 2.2), a history of landscape deterioration under the impacts of pollution, and a history of environmental research conducted around the selected polluters. The amount of information included in this chapter for each polluter depends on its availability to the international scientific community. We do not repeat details easily available from review papers (e.g., on Harjavalta, Monchegorsk, and Sudbury), but we do include more data for less well-known polluters, especially from sources published in national languages. Historical information is referenced only in cases of discrepancies between different data sources.

Emission data are of vital importance for understanding changes in the polluted environment, conducting comparative analyses and exploring dose-response relationships (Ruotsalainen & Kozlov 2006; Zvereva et al. 2008). These data are also necessary for re-assessment of regional and global emissions from anthropogenic sources (Nriagu & Pacyna 1988; Pacyna & Pacyna 2001). Therefore, every effort was made to obtain emission data from both published and unpublished sources for

Table 2.2 Temperature and precipitation at the study areas

Polluter	Mean temperatures, °C January	July	Annual precipitation, mm
Apatity	−13.2	13.6	640
Bratsk	−20.5	17.4	357
Harjavalta	−6.8	16.4	545
Jonava	−5.2	16.8	630
Kandalaksha	−13.7	14.3	519
Karabash	−16.4	15.4	666
Kostomuksha	−12.8	15.0	580
Krompachy	−3.6	19.2	613
Monchegorsk	−13.8	14.1	561
Nadvoitsy	−11.7	14.1	566
Nikel/Zapolyarnyy	−10.9	11.7	499
Norilsk	−28.9	13.8	528
Revda	−15.7	17.4	546
Straumsvík	−11.7	14.1	569
Sudbury	−11.9	19.1	811
Volkhov	−10.8	16.7	652
Vorkuta	−24.8	14.3	437
Žiar nad Hronom	−3.3	18.7	644

Climatic data were estimated using *New_LocClim* (FAO 2006).

all the polluters involved in our analysis. Since emission data are very diverse due to a variety of methods for their estimation and reporting, we referenced each value in Tables 2.4–2.24. If values that differ from each other by more than 7% were reported for the same year, they were all included in our tables. If the values differ less than by 7%, then the value reported with higher accuracy was included in the table (i.e., 0.83 was preferred over 0.8).

Importantly, the data on both ambient concentrations of pollutants and, later on, emission of pollutants in industrial cities of the USSR (before 1990) and of the Russian Federation (since 1991) have been summarised in annual reports by the Voeikov Main Geophysical Observatory (St. Petersburg) from 1966 until 1995, and by the Research Institute of Ambient Air Protection (St. Petersburg) since 1996. These low-circulation reports (100–250 copies, published in Russian) were, until 1987, 'for the restricted use only', with numbered copies deposited into specially authorised departments of the main libraries, and public access to old reports was allowed only in 2007. However, even the accessible reports (for the years 1988–2005) remain unknown to the majority of environmental scientists, leading to large uncertainties in estimation of local and regional depositions of pollutants (Boyd et al. 2009). We were lucky to obtain access to most of these reports (Berlyand 1967, 1968, 1969, 1970, 1971, 1972, 1973, 1974, 1975, 1976, 1979, 1980, 1981, 1982, 1983, 1984, 1985, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1994; Milyaev & Nikolaev 1996; Milyaev et al. 1997a, b, 1998, 1999, 2000, 2001, 2002, 2003; Milyaev & Yasenskij 2004, 2005, 2006). For reasons of brevity, these reports are later referred to as 'Emissions of pollutants in Russia (1966–2005)'. Since these reports combine emissions of all polluters within a city, the data should be used with caution, especially for sulphur dioxide and nitrogen oxides that are emitted by many industries. Still, these values are good approximations for the giant polluters (such as Monchegorsk, Nikel, or Karabash, that produce over 95% of a town's emissions), as well as for pollutants associated with specific industrial processes (such as fluorine-containing substances emitted by aluminium industries). Amounts of both production and emission are reported in metric tons (i.e., 1,000 kg; abbreviated 't' hereafter).

The data on pollution loads and the extent of the contaminated territory are even less uniform than the emission data. Therefore, we have chosen to report them in their original form. We paid special attention to the information on the spatial extent of the contaminated territory, i.e., the area with statistically significant increases in pollution load relative to the regional background level. Since this area was often measured from published maps showing 'pollution zones', criteria for defining these zones vary across the selected polluters.

We provide several estimates reflecting (to a certain extent) the level of knowledge on both environmental contamination around the selected polluters and biotic effects attributable to pollution (Table 2.3). The number of publications known to us is counted from an extensive collection of reprints accumulated by M. Kozlov and E. Zvereva over 25 years of research on pollution ecology; it recently included approximately 5,000 publications reporting pollution effects on terrestrial biota. Potential publications were searched using the ISI Web of Science and several more databases. The publications in Russian were identified by surveying the abstract

Table 2.3 Amount and quality of available information on environmental impact of the selected polluters

Polluter	Number of publications		Contamination[a]		Biotic effects[a]		Number of effect sizes used in meta-analyses[b]			
	Total[c]	ISI[d]	A	Q	A	Q	1	2	3	4
Apatity, Russia: power plant	3	1	1	3	1	3	0	0	1	2
Bratsk, Russia: aluminium smelter	50	0	2	3	2	2	1	0	29	5
Harjavalta, Finland: nickel-copper smelter	200	57	3	3	3	3	3	5	46	13
Jonava, Lithuania: fertiliser factory	60	9	2	3	2	3	1	0	0	3
Kandalaksha, Russia: aluminium smelter	30	6	1	2	1	1	1	1	5	9
Karabash, Russia: copper smelter	80	8	2	3	2	3	0	5	5	2
Kostomuksha, Russia: iron pellet plant	100	7	3	3	2	2	4	5	1	13
Krompachy, Slovakia: copper smelter	20	8	2	2	1	2	0	0	0	0
Monchegorsk, Russia: nickel-copper smelter	1,000+	91	3	3	3	3	10	5	58	80
Nadvoitsy, Russia: aluminium smelter	0	0	0	–	0	–	0	0	0	0
Nikel, Russia: nickel-copper smelter (and ore-roasting plant in Zapolyarnyy)	100	40	2	3	2	3	6	3	6	24
Norilsk, Russia: nickel-copper smelters	80	17	2	3	1	1	4	0	0	0
Revda, Russia: copper smelter	300	12	3	3	3	3	4	5	17	21
Straumsvík, Iceland: aluminium smelter	10	0	1	3	1	1	0	0	0	0
Sudbury, Canada: nickel-copper smelter	100	20	3	3	2	3	1	5	3	0
Volkhov, Russia: aluminium smelter	5	1	1	2	1	3	0	0	10	0
Vorkuta, Russia: power plant	40	8	2	2	2	2	0	0	0	4
Žiar nad Hronom, Slovakia: aluminium smelter	80	11	2	2	2	2	0	5	18	3

Numbers of publications may overestimate the level of knowledge on environmental effects due to repeated publication of the same results by several Russian research groups. This especially concerns studies conducted near Kandalaksha, Karabash, Kostomuksha and Monchegorsk.

[a] Evaluation is based on publications available to the authors. Amount of published information (A) scored as: 0 – absent, 1 – insufficient; 2 – sufficient to outline the general picture; 3 – sufficient to represent the detailed picture. Quality of published information (Q), in terms of sampling design (number and distribution of study sites), applied methodology, statistical analysis and presentation form, scored as: 1 – unsatisfactory; 2 – moderate; 3 – high (an overall impression based on all available data sources).

[b] Publication coded as follows: 1 – abundance and diversity of soil fungi (Ruotsalainen & Kozlov 2006), 2 – diversity of vascular plants (Zvereva et al. 2008), 3 – abundance and diversity of arthropods (Zvereva & Kozlov 2009), 4 – growth and reproduction of vascular plants (Roitto et al. 2009).

[c] Only scientific publications were counted (grey literature included, but newspaper reports and web-based data in HTML format excluded); all values exceeding ten are approximate; for the efforts taken to obtain relevant publications, consult text (Section 2.2.1).

[d] ISI Web of Knowledge was searched for location of the polluter, its name, and the type of the industry; all searches were conducted between 25 December 2007 and 10 January 2008.

journal *Nature protection* (1990–2007; code 72 in the series of monthly abstract journals published by the All-Russian Institute of Scientific and Technical Information in Moscow). We also checked reference sections of all obtained data sources, and asked colleagues from many countries for assistance in locating grey literature and publications in national languages. The review of publications describing the effects of each of the polluters on terrestrial biota are by no means exhaustive; additional publications can be located using review papers published by our team (Ruotsalainen & Kozlov 2006; Kozlov & Zvereva 2007a; Zvereva et al. 2008; Zvereva & Kozlov 2009; Roitto et al. 2009).

Although a detailed investigation of the perception of environmental and health problems caused by industrial pollution is outside the scope of our study, we still found it interesting to give a brief overview of materials reflecting the degree of public awareness of local environmental problems. For reasons of simplicity, in this review we used a dual referencing system: all individual data sources, such as newspaper reports or individual web-based documents, are included in the list of references, However, overall impressions obtained by surveying some web sites, or small pieces of web-based information that cannot be attributed to an individual author, are referred to by short URLs inserted into the text. All websites mentioned in this chapter were visited between 20 December 2007 and 19 January 2008. An absence of information can be seen as an absence of public interest in local environmental problems.

2.2.2 Descriptions of the Polluters

2.2.2.1 Apatity, Russia: Power Plant (Color Plates 1–3 in Appendix II)

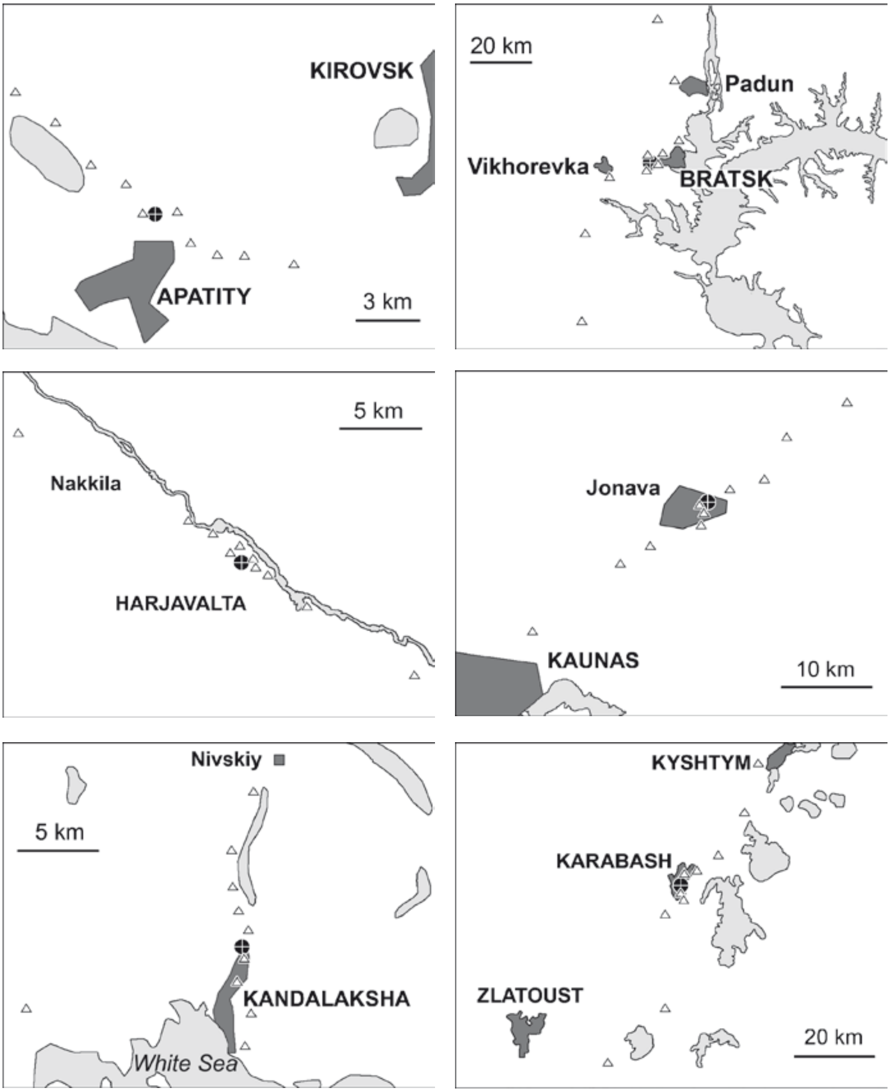
Location and Environment

Apatity (population 62,600; data from 2007) is a town in the Murmansk Region, located between Imandra Lake and the Khibiny Mountains 160 km south of Murmansk (Fig. 2.2). Originally it was surrounded by mixed forests of Scots pine (*Pinus sylvestris*) and mountain birch[1] (*Betula pubescens* subsp. *czerepanovii*), usually with dwarf shrub and moss cover; stands with ground lichens were relatively infrequent.

Pre-industrial History

The earliest settlements on Imandra Lake, 15 km east of the current location of Apatity, appeared 7–8,000 years ago. In 1574, a country churchyard, with six huts and 40 inhabitants subsisting on fishing and hunting, existed at about the same locality.

[1]Jonsell (2000) considered mountain birch, *Betula pubescens* subsp. *czerepanovii* (Orlova) Hämet–Ahti, an ecological form of white birch (*Betula pubescens*), not a distinct taxon.



Figs. 2.2–2.7 Distribution of study sites (triangles) around investigated polluters (black circles with white cross inside). Names of larger settlements (usually towns) are capitalised. **2.2**, power plant in Apatity, Russia; **2.3**, aluminium smelter in Bratsk, Russia; **2.4**, nickel-copper smelter in Harjavalta, Finland; **2.5**, fertilising factory in Jonava, Lithuania; **2.6**, aluminium smelter in Kandalaksha, Russia; **2.7**, copper smelter in Karabash, Russia

The first permanent settlement at the current location of the city appeared in 1916 in connection with the building of a railway from St. Petersburg to Murmansk. Colonisation started in 1924 when the village of Byelorechenskij was established close to the place where the power plant was later built. Apatity was granted town status in 1966.

Industrial History

The intensive growth of Apatity (from seven inhabitants in 1926 to 4,000 in 1939 and 15,200 in 1959) was associated with the development of the apatite mining and processing industry. The main employer of Apatity is the joint stock company 'Apatit', the largest mining and concentrating enterprise in Europe.

The coal-fired power plant ('Kirovskaya GRES', now named 'Apatitskaya TEC') was launched in 1959 and reached its full capacity in 1961. For the first 2 decades, it mostly produced electricity (up to 37% of the total output of the Murmansk region), but since the late 1970s, it is used almost exclusively for heating the town. The power plant employed 983 people in 2003, but only 520 people in 2005; it achieves peak capacity (80 MWt) during the winter, when daily coal consumption reaches 2,800–3,000 t. In the summer, the daily coal consumption is around 650 t and the capacity is 10 MWt. The station mainly uses coal from Inta, Northern Ural (sulphur content 1.5–1.9%), but sometimes from Spitsbergen or Khakassia (sulphur content 0.7–1.0%).

Emissions Data

The power plant is the only local emitter of sulphur dioxide and some metals, such as iron, zinc, chromium, cadmium and lead (Golubeva 1991). The station contributed 99.0% of the sulphur dioxide and 75.4% of the mineral dust to overall emissions of Apatity (summarised in Table 2.4).

Pollution Loads and the Extent of the Contaminated Territory

Ambient concentrations of pollutants in Apatity have been monitored since 1972; the peak reported values were 1.4 mg/m^3 of dust in 1972 and 1.43 mg/m^3 of SO_2 in 1982 (Emissions of pollutants in Russia 1966–2006). During the period 1987–1989, annual depositions of sulphur and nitrogen in Apatity were 3,100 and 400 kg/km^2, respectively (Vasilenko et al. 1991). Concentrations of chromium, arsenic and lead in the leaves of the speckled alder (*Alnus incana*) in 1992 were below the detection limit (10 mg/kg), even within a few hundred meters of the power plant. Foliar concentrations of nickel, copper and zinc showed no relationship to the distance from the polluter. The peak concentrations of strontium were detected 4–7 km northwest of the power plant and were obviously associated with dust contamination from tailing ponds of the apatite and nepheline-processing factory (located 400–800 m from these sites). Foliar concentrations of iron appeared to be a good measure of pollution load; they exceeded the background level by a factor of 3 within 2 km of the power plant and approached regional background levels at about 5 km (Kozlov 2003). Consistently, soil contamination was detected only within approximately 2 km^2 east of the power plant (Kalabin 1999). On the other hand, from 1986 to 1991 a doubling of pollutant deposition (relative to the regional background) was recorded for the 800 km^2 around Apatity (Prokacheva et al. 1992).

Table 2.4 Aerial emissions (t) from industrial enterprises at Apatity, Russia

Year	Dust	SO_2	CO	NO_x
1972	14,600	51,800	–	–
1973	14,600	51,100	–	12,800
1974	14,600	51,100	–	12,800
1975	18,250	51,100	–	12,800
1978	19,500	25,500	–	2,100
1979	17,400	31,300	–	3,300
1980	17,700	31,200	10	3,200
1981	14,400	21,500	200	2,900
1982	13,900	31,800	100	2,500
1983	15,800	30,800	5,000	2,700
1984	19,000	36,900	4,900	2,800
1985	19,700	35,300	5,500	3,300
1986	15,200	31,000	8,300	4,500
1987	16,300	36,400	800	4,500
1988	14,400	30,700	900	4,100
1989	13,800	29,400	600	2,700
			4,900[a]	3,200[a]
1990	16,100	31,900	700	3,500
			9,200[a]	4,400[a]
1991	17,600	28,200	300	3,200
			8,800[a]	4,100[a]
1993	10,200	21,400	700	6,900
1994	7,100	14,600	300	5,600
1995	7,400	11,800	400	5,500
1996	7,300	14,700	200	5,100
1997	8,900	16,200	1,100	5,300
1998	8,600	17,900	700	4,500
1999	8,100	16,800	500	4,200
2000	7,300	16,200	300	4,000
2001	7,200	14,300	300	4,200
2002	5,800	12,000	200	3,900
2003	5,300	7,300	200	3,600
2004	6,000	10,300	100	3,900
2005	5,100	8,200	100	3,300

Non-referenced values were extracted from Emissions of Pollutants in Russia (1966–2006).
Other data sources:
[a] Kryuchkov (1993b).

Habitat Transformation due to Human Activity

Forests located 1–3 km from the power plant (please see color plate 3 in Appendix II) are dominated by mountain birch and speckled alder due to selective logging of conifers during the expansion of the settlement (between the 1930s and 1970s). Field layer vegetation is sparse, most likely due to both recreational activities (picking of berries and mushrooms) and dust contamination from the apatite-processing plant.

Brief History of Environmental Research

The data on the environmental impact of the power plant at Apatity are restricted to a study modelling the spatial distribution of sulphur dioxide (Baklanov et al. 1993), a report mentioning (but not quantifying) the contribution of the power plant to soil contamination by some metals (Golubeva 1991), and a paper reporting the results of long-term (1991–2001) monitoring of the population density of a tiny moth, *Phyllonorycter strigulatella* (Lienig et Zeller) (Lepidoptera, Gracillariidae), whose larvae develop in the leaves of the speckled alder (Kozlov 2003).

Perception of the Environmental Situation

The local population is most worried by the health effects of dust from tailing ponds of the apatite-processing factory, which affects the quality of ambient air in the city (especially on windy days) and contaminates drinking water (www.liga-rf.ru).

2.2.2.2 Bratsk, Russia: Aluminium Smelter (Color Plates 4–6 in Appendix II)

Location and Environment

Bratsk is a large (population 253,200; data from 2007) industrial city in the Irkutsk Region, located on the Angara River near the vast Bratsk Reservoir, 490 km North of Irkutsk (Fig. 2.3). Bratsk is surrounded by southern taiga forests (please see color plate 5 in Appendix II) consisting mostly of Scots pine (56%) and common birch (*Betula pendula*) (22%); other abundant trees are Siberian larch (*Larix sibirica*), Siberian spruce (*Picea abies* ssp. *obovata*), and Siberian fir (*Abies sibirica*).

Pre-industrial History

The area surrounding Bratsk has long been populated by Buryats who subsisted mostly from hunting. Bratsk was founded in 1631, when the stockaded fort was built at the confluence of the Oka and Angara rivers (now submerged by the Bratsk reservoir). In 1702, 128 homesteads were recorded in the Bratsk area. In 1805, the newly established Bratsk administrative unit had 5,210 inhabitants. In 1948, the regional centre, the old village of Bratsk, had 2,247 inhabitants. Town status was granted in 1955.

Industrial History

The railway reached Bratsk in 1947. The construction of the Bratsk dam and the hydroelectric station was completed in 1961. Construction of the aluminium smelter started in 1961. Production of aluminium was launched in 1966, but extension of the facilities continued until 1976; annual production reached 850,000 t in the late 1990s (US Geological Survey 1999). In 2006, the smelter employed approximately 5,000 people and produced 983,000 t of primary aluminium (30% of the aluminium production in Russia and 4% of the world's output), totalling 30,000,000 t of aluminium since its launch. In the early 1990s, the smelter implemented an ecologically oriented modernisation program, which will continue until 2012 (Ditrikh 2001). The city also houses large-scale timber processing industries and several coal-fired power plants.

Emissions Data

Although the emission of pollutants from all industries in Bratsk has been reported since 1970 (Table 2.5), emissions from the aluminium smelter were first estimated in 1980 (Ditrikh 2001). All emissions of fluorine-containing gases reported for the city of Bratsk (Emissions of pollutants in Russia 1966–2006) were attributed to the aluminium smelter; contributions from other sources to HF emissions is less than 0.1%, and to fluorine-containing dust emissions is approximately 6% (Lyubashevsky et al. 1996). Data on other pollutants are scarce. Bezuglaya et al. (1991, fig. 2.104) indicated that during the period 1984–1998, emissions of nitrogen oxides from the aluminium smelter were approximately 300 t, i.e., 5% of the overall emissions in Bratsk. Lyubashevsky et al. (1996), referring to local authorities, reported (for an unknown year, presumably 1992 or 1993) emissions of 25,358 t of dust, 3,968 t of SO_2, 2,448 t of HF, 2,808 t of fluorine-containing dust (it remains unclear, whether this value is included in an overall estimate of dust emission given above), 274 t of NO_x, and 107,199 t of CO. Importantly, these values (totalling 142,055 t) suggest substantially higher emissions than reported by Ditrikh (2001).

Pollution Loads and the Extent of the Contaminated Territory

Ambient concentrations of pollutants in Bratsk have been monitored since 1969; the peak reported values were 3.18 mg/m^3 of SO_2 in 1975, 1.39 mg/m^3 of NO_x in 1971, 7.0 mg/m^3 of dust in 1970, and 0.44 mg/m^3 of HF in 1978 (Emissions of pollutants in Russia 1966–2006).

The peak annual depositions of fluorine near the polluter were 7,200 kg/km^2 in the early 1980s and 5,000 kg/km^2 in the early 1990s (Morshina 1986; Davydova 2001), i.e., 300–1,000 times as high as the regional background. The increase in sulphur deposition was less extreme, with peak values exceeding the background by a factor of 10–30 (Davydova 2001). In 1987–1989, annual depositions of sulphur and nitrogen in Bratsk were 1,100 and 500 kg/km^2, respectively (Vasilenko et al. 1991).

The deposition of airborne pollutants in the 1980s exceeded the regional background within approximately 100 km of Bratsk (Morshina 1986). These data suggest that an area of 25,000–30,000 km^2 was contaminated by smelter emissions; however, the larger part of this territory (with 3–25 times excess fluorine deposition and 2–10 times excess sulphur deposition over the regional background) did not

Table 2.5 Aerial emissions (t) from industrial enterprises at Bratsk, Russia

Year	Total[a]	Dust	SO_2	CO	NO_x	F-containing dust	HF
1970	–	–	–	–	–	–	730
1971	–	5,500	8,400	–	–	–	2,200
1972	–	16,400	25,600	–	–	–	7,300
1973	–	51,100	40,150	–	9,100	3,500	2,800
1974	–	73,000	43,800	186,200	14,600	–	4,000
1975	–	73,000	43,800	175,200	14,600	–	4,000
1978	–	51,200	17,500	183,100	8,300	–	5,490
1979	–	49,900	21,600	188,000	9,100	–	5,100
1980	181,598[a]	45,500	18,200	165,500	7,400	–	6,100
1981	172,779[a]	57,800	17,500	152,700	5,000	–	2,600
1982	168,981[a]	60,200	22,400	147,100	5,400	4,000	3,200
1983	161,995[a]	57,600	23,900	148,200	5,600	3,455	2,862
1984	149,925[a]	51,600	23,800	136,800	5,400	3,355	2,960
1985	132,596[a]	51,000	22,300	118,200	5,100	3,061	2,448
1986	125,999[a]	44,400	21,100	114,800	4,600	2,970	2,240
1987	111,572[a]	41,900	22,400	101,700	4,700	2,652	2,020
1988	99,465[a]	41,300	20,700	85,400	5,700	–	1,960[b]
1989	55,171[a]	42,400	22,700	50,900	6,100	2,652	2,020
1990	52,947[a]	41,300	16,700	54,700	7,500	–	2,020
1991	73,386[a]	50,800	18,500	59,300	7,600	3,295	2,155
1992	92,998[a]	–	–	–	–	–	–
1993	78,297[a]	41,600	15,900	56,300	5,800	–	2,463
1994	73,843[a]	36,700	13,800	49,000	4,800	–	2,069
1995	64,487[a]	–	–	–	–	–	2,070
1996	58,609[a]	23,700	10,300	46,600	8,300	–	1,714
1997	46,642[a]	20,200	8,400	45,300	7,200	–	1,453
1998	43,556[a]	22,800	9,700	45,800	7,200	–	1,324
1999	42,680[a]	20,800	8,900	45,300	7,500	–	1,299
2000	82,426[a]	25,900	10,300	75,000	6,400	–	1,456
2001	–	21,300	9,000	62,500	5,600	–	1,280
2002	–	22,200	7,600	52,000	6,100	–	1,070
2004	–	16,300	5,900	49,300	7,300	–	1,037
2005	–	19,400	7,200	55,200	8,500	–	1,110

Non-referenced values were extracted from Emissions of Pollutants in Russia (1966–2006); emissions of SO_2 from the aluminium smelter comprise approximately 18% of the total emissions reported for Bratsk (proportion based on data of Lyubashevsky et al. 1996).
Other data sources:
[a] Ditrikh (2001), values refer to the aluminium smelter only.
[b] Bezuglaya et al. (1991).
Note added in proof: Detailed information on the emissions of Bratsk aluminium smelter during 1980–2001 is published by Pavlov (2006).

exhibit visible signs of environmental damage. During the period 1986–1991, a doubling of pollutant deposition (relative to the regional background) was recorded for 3,000 km^2 around Bratsk (Prokacheva et al. 1992). Detectable soil contamination by fluorine extended up to 15 km (Morshina 1986), with a peak value of 3,400 mg/kg (Sataeva 1991). On the basis of pollutant deposition and changes in vegetation structure, Davydova (2001) outlined zones of extreme (13.9 km^2), strong (82.5 km^2), moderate (200 km^2), and modest (316 km^2) impact.

Habitat Transformation due to Human Activity

Forests have been cut around Bratsk for centuries, while the impact of agriculture was negligible until the 1950s. Recently, pollution has been the leading factor in habitat transformation, although the contribution of recreational activities is also detectable (Alpatov et al. 2001).

The first signs of forest damage became apparent in 1968, when 1.36 km^2 of Scots pine stands died on the slopes of Mogrudon hill, situated near the smelter. Forest dieback increased to 15–20 km^2 by 1976, 50–75 km^2 by 1985, and 100–150 km^2 by the early 2000s. The extent of damaged forests reached 800 km^2 by 1985 (Ugrjumov et al. 1996) and 1,000–1,500 km^2 by the late 1990s (Runova 1999); another data source reported damage to 1,400 km^2 of forests by the early 1980s (Mikhailova 2003) and 2,000 km^2 by the mid-1990s (Mikhailova 1997). Davydova (2001) estimated that landscapes within approximately 70 km were affected by the emissions.

The aluminium smelter shares the responsibility for adverse environmental effects with power plants and timber-processing industries, emitting 82% of the sulphur dioxide released in Bratsk. Although fluorine contamination may cause more pronounced environmental effects than sulphur dioxide, it is estimated that only 41.5% of forest damage within 50 km of Bratsk is due to emissions from the aluminium plant (Lyubashevsky et al. 1996).

In spite of the extreme pollution loads, we have not found industrial barrens (bleak open landscapes evolved due to deposition of airborne pollutants, with only small patches of vegetation surrounded by bare land) around the Bratsk smelter (Kozlov & Zvereva 2007a). However, trees are nearly absent within the zone of extreme impact, which is mostly covered by herbaceous vegetation and low-stature alder and willow bushes, exhibiting clear signs of pollution-induced damage, i.e., dwarfed growth forms and chlorosis (please see color plate 6 in Appendix II). The surrounding zone of strong impact is mostly covered by white birch (*Betula pubescens*) and European aspen (*Populus tremula*); surviving Scots pine and Siberian spruce often have dead upper canopies and stunted growth forms (Davydova 2001).

Brief History of Environmental Research

All publications on the environmental impact of the Bratsk aluminium smelter, including five monographs (Rozhkov & Mikhailova 1989; Lyubashevsky et al. 1996; Ugrjumov et al. 1996; Runova 1999; Pavlov 2006), are in Russian. The book by Rozhkov and Mikhailova (1992) was translated to English. The vast majority of publications do not report quantitative data in a form suitable for meta-analysis (Table 2.3). Especially disappointing is a book by Lyubashevsky et al. (1996), which lists a large number of biotic effects, such as smaller size and germinability of the seeds of white and common birches, a decline in species richness of lichens, changed growth of several herbaceous species, and changes in abundances of different groups of insects. However, this book did not provide either supporting numerical information or the results of statistical tests. Majority of these raw data have never been published (N. Lyubashevsky 2006 and M. Trubina, personal communication, 2006) and are, in fact, lost to science.

The very first studies of the environmental impacts of the aluminium smelter on forest ecosystems were conducted in the early 1970s by researchers from the Siberian Institute of Plant Physiology and Biochemistry, Irkutsk. In particular, they documented growth of conifers (Sokov & Rozhkov 1975) and listed xylophagous insects in damaged forests (Anisimova 1989). Since 1977, integrated research of the forests affected by emissions from both the aluminium smelter and the timber-processing industry has been conducted (for nearly 20 years) by scientists from the Forest Technical Academy in St. Petersburg. They have documented changes in forest vitality, including decreases in the vertical growth and radial increment of conifers, suppression of regeneration of conifers with simultaneous increases in the density of birch and aspen seedlings, and quantified damage to woody plants by insect herbivores (Kataev et al. 1981; Golutvin et al. 1983; Popovichev & Golutvin 1983; Selikhovkin 1992, 1995). Decreases in the increment of Scots pine near Bratsk (detected by dendrochronological analysis) started in the 1960s and were therefore associated with the beginning of the pollution impact (Lairand et al. 1979). Since the mid-1990s, a research team from Bratsk University has monitored forest damage and developed silvicultural measures for impacted forests (Ugrjumov et al. 1996; Alpatov et al. 2001).

Perception of the Environmental Situation

Bratsk was declared an ecological disaster zone in 1993, and the government of the Russian Federation developed plans to improve the situation from 1994–2000. In spite of a substantial decrease in emissions (Table 2.5), the Chekanovskiy settlement (located 1.5 km northeast of the smelter) was evacuated in 2001 due to repeated health emergencies. Bratsk is listed by the 2004 report of the Central Geophysical Laboratory in St. Petersburg among the ten most polluted Russian cities (english.pravda.ru), and by the report of the Blacksmith Institute (2007) among the 30 most polluted places in the world in the category 'petrochemicals'. The most acute environmental problems have recently been identified as contamination of drinking water by mercury, and not with air pollution (www.pollutedplaces.org).

2.2.2.3 Harjavalta, Finland: Nickel-Copper Smelter (Color Plates 7–11 in Appendix II)

Location and Environment

Harjavalta is a small (population 7,700; data from 2007) town in Western Finland, 170 km northwest of Helsinki (Fig. 2.4). Harjavalta is situated on an esker that runs to the southeast of the smelter. The region is part of the southern boreal coniferous zone, with the forest consisting mainly of Scots pine (please see color plate 8 in Appendix II). According to the Finnish classification, the forest along the esker varies from the *Vaccinium* to the *Calluna* type.

Pre-industrial History

The Harjavalta region has been populated since the Iron Age, with the first signs of human settlement dating back to about 1500 BC. Written records mentioning the village of Harjavalta begin in the AD 1400s. Harjavalta was established as a municipality in 1869 and an independent parish in 1878, when it included 1,600 inhabitants. Telephones and railroads reached Harjavalta in the late nineteenth century, but Harjavalta remained a typical countryside village until 1944. By 1950, Harjavalta had a population of 6,000. Town status was granted in 1977.

Industrial History

The Outokumpu copper plant was moved to Harjavalta from Imatra in 1944 (at the end of World War II) because of the proximity of Imatra to the Russian border; it started operations in 1945. The Kemira sulphuric acid plant was launched in 1947 and the nickel smelter in 1960; recently, this industrial area has hosted 13 different firms (Heino & Koskenkari 2004). Originally part of Outokumpu, a Finnish company, the copper business is now owned by Boliden (since 2003) and the nickel business by Norilsk Nickel (since 2007). The copper smelter has a nominal annual capacity of 160,000 t. Sulphur is recovered and sold as sulphuric products. The nickel smelter, operating on a tolling basis, produces nickel matte.

Emissions Data

Accurate emissions data from the Harjavalta smelters (Table 2.6) have been available through Outokumpu reports and the web-site, as well as from the documents of the Finnish Ministry of Environment, since the mid-1980s; they were partially published in many research reports, including those by Nieminen et al. (2002) and Kiikkilä (2003). Estimates of dust emissions for 5-year periods starting with the beginning of smelting have been published by Nieminen et al. (2002) and are included in Table 2.6; for a detailed history of emissions and for annual production-based estimates of dust emissions (not included in Table 2.6), consult Nieminen (2005). Data on annual emissions of sulphur dioxide in the early 1970s are contradictory: 20,000 t was reported by Levula (1993), while Laaksovirta and Silvola (1975) indicated 4,800 t.

Data from 1990 demonstrated that smelters contributed 98.7% of the sulphur dioxide, 90% of the nitrogen oxides (with annual emissions of 180 t), 92.7% of the dust

Table 2.6 Annual emissions (t) from Harjavalta smelters, Finland

Year	Dust	SO_2	Cu	Ni	Pb	Zn	Cd	As
1945	–	30,000[a]	–	–	–	–	–	–
1947	–	35,000[b]	–	–	–	–	–	–
1945–1949	478[c]	–	–	–	–	–	–	–
1950	–	10,000[a]	–	–	–	–	–	–
1950–1954	534[c]	–	–	–	–	–	–	–
1955–1959	784[c]	–	–	–	–	–	–	–
1960–1964	1,195[c]	–	–	–	–	–	–	–
1965–1969	632[c]	–	–	–	–	–	–	–
1970	–	20,000[a]	–	–	–	–	–	–
1970–1974	548[c]	–	–	–	–	–	–	–
1975–1979	778[c]	–	–	–	–	–	–	–
1980–1984	903[c]	–	–	–	–	–	–	–
1984	1,100	11,500	300	70	50	200	–	–
1985	1,100	7,800	98	47	55	216	1.7[d]	15[d]
1986	1,200	7,530	126	46	60	232	7.1[d]	17[d]
1987	1,800	6,860	140	90	94	162	3.9[d]	19[d]
1988	1,000	8,500	104	45	48	103	3.2[d]	19[d]
1989	1,000	9,500	80	33	70	190	3.6[d]	22[d]
1990	960	8,800	80	31	80	160	4.2[d]	28[d]
1991	640	5,200	80	15	45	90	1.6[e]	–
1992	280	4,800	60	10	9.0	12	1.0[e]	–
1993	250	4,700	50	7.0	6.0	11	0.9[e]	10[e]
1994	190	5,000	40	6.0	3.0	6.0	0.6[e]	5.0[e]
1995	70	3,270	17	1.4	0.5	1.7	0.0[e]	0.2[e]
1996	195	3,243	49	1.2	1.9	5.3	0.2[e]	4.2[e]
1997	355	2,980	69	2.9	3.9	14	0.3[e]	10[e]
1998	132	3,041	23	1.7	2.4	6.1	0.4	10
1999	48	3,397	5.9	0.8	1.0	4.2	0.3	1.8
2000	36	3,002	6.6	1.2	0.2	1.1	0.1	0.8
2001	50	3,387	7.4	0.8	0.7	3.0	0.4	1.6
2002	55	3,300	11.6	0.6	0.4	1.5	0.1	0.5
2003	–	3,000	6.0[f]	0.6[f]	0.3[f]	0.9[f]	–	0.4[f]
2004	–	2,900	–	–	–	–	–	–
2005	–	2,850	–	–	–	–	–	–

Non-referenced values were obtained from Outokumpu Harjavalta Metals Ltd. Other data sources:
[a] Levula (1993).
[b] Poutanen and Kuisma (1998).
[c] Nieminen et al. (2002).
[d] Harjavallan Kaupunki (1991).
[e] Helmisaari (2000).
[f] Nieminen (2005).

and 99.5% of the heavy metals emissions at Harjavalta (Harjavallan Kaupunki 1991). However, before the closure of the fertiliser factory in 1989, the emissions share of the smelter for nitrogen oxides was much lower; 125 t emitted in 1978 constituted only 17.2% of the total emissions at Harjavalta (Helmisaari 2000). Emissions of NO_2 in 2002 were 250 t (Outokumpu Harjavalta Metals Ltd.). In 2002, Outokumpu claimed the smelter to be ‘among the cleanest in the world’.

Pollution Loads and the Extent of the Contaminated Territory

Long-term pollution impacts resulted in soil contamination by metals, with peak recorded values of 49,000 mg/kg of copper, 913 mg/kg of nickel, 58 mg/kg of arsenic, 620 mg/kg of zinc, and 204 mg/kg of lead (Helmisaari et al. 1995; Derome & Nieminen 1998; Uhlig et al. 2001; Salemaa et al. 2001; Nieminen et al. 2002; Nieminen 2004). However, due to a substantial decline in emissions, both deposition of pollutants and ambient concentrations of sulphur dioxide have been very low recently. For example, average ambient concentrations of sulphur dioxide near the smelter in 2001–2002 were 0.004–0.006 mg/m^3 (Outokumpu Harjavalta Metals Ltd.), i.e., well below sanitary limits.

The polluted area, defined by the accumulation of copper in moss bags exceeding the background level by a factor of 5 or more (Hynninen 1986), in 1981–1982 was 70 km^2. In 1995, the area contaminated by copper (over 8 mg/kg in green mosses) was 107 km^2 (Kubin et al. 2000).

Habitat Transformation due to Human Activity

The heathland Scots pine forests in the immediate vicinity of the smelter died during the first years of industrial activity, but they were left uncut until the mid-1950s (Poutanen & Kuisma 1998). The very first evaluation, conducted at the beginning of the 1970s, classified 8.8 km^2 as a lichen desert, i.e., the area where epiphytic lichens disappeared due to the pollution impact. Visible damage to Scots pine was detected within approximately the same area, and another 52 km^2 area was classified as a transitional zone (Laaksovirta & Silvola 1975).

In the mid- to late 1950s, the dying forest around the smelter was restored by planting Scots pine seedlings, which had a high rate of survival but stunted growth. They have formed a kind of forest with unusually open canopies and dead or nearly dead ground layer vegetation (please see color plates 9 and 11 in Appendix II). The overall extent of barren and semi-barren habitats around Harjavalta is now approximately 0.5 km^2 (Kozlov & Zvereva 2007a).

Brief History of Environmental Research

The first scientific report known to us about the environmental effects of the Harjavalta smelters is the paper by Laaksovirta and Silvola (1975). Many of the studies conducted near Harjavalta were based on a poorly replicated sampling design, with four study sites, each representing a different pollution load. The studies cover soil microbiota, invertebrates (mostly epigeic fauna and insect herbivores), the structure of plant communities, the growth and vitality of Scots pine, and the performance of insectivorous birds (for a review and references, consult Kiikkilä 2003). Recent declines in emissions have already resulted in ecosystem recovery, which was detected by monitoring bird communities (Eeva & Lehikoinen 2000).

Perception of the Environmental Situation

The Harjavalta smelter was removed from a ‘hot spot’ list of top Baltic polluters in 2003. A census by the Association of Finnish Local and Regional Authorities in 2004 clearly showed that Harjavalta’s image has changed greatly due to a significant decrease in emissions since 1990; it is no longer perceived as a polluted little town (Rintakoski 2004). In spite of several accidents reported in newspapers (www.turunsanomat.fi), local inhabitants pay little attention to environmental contamination.

2.2.2.4 Jonava, Lithuania: Fertiliser Factory (Color Plates 12–14 in Appendix II)

Location and Environment

Jonava (population 34,500; data from 2007) is located in the central part of Lithuania, 30 km northeast of Kaunas (Fig. 2.5). Before the onset of pollution, Scots pine (50%), Norway spruce (*Picea abies* ssp. *abies*) (23%), common birch and black alder (*Alnus glutinosa*) prevailed in the local forests (Armolaitis 1998).

Pre-industrial History

Jonava (founded in 1740) was an estate until the mid-eighteenth century, owned by the Kosakowski family. In 1750, Jonava received town and market rights, but it did not develop into a city. In 1923, proper city rights were granted, but no substantial growth had occurred prior to World War II.

Industrial History

Construction of the nitrogen fertiliser factory ‘Achema’ (formerly ‘Azotas’) started near Jonava, at the confluence of the rivers Neris and Sventoji, in 1962. Production of synthetic ammonia was launched in 1965; development of the factory and the launching new departments continued until 1973. The factory became the ‘Achema’ stock company following privatisation in 1994. Recently, the plant has become the biggest producer of nitrogen fertilisers in Lithuania, Latvia and Estonia. It employs 1,600 workers and produces ammonia, ammonium nitrate, urea ammonium nitrate solution, and many other chemicals.

Emissions Data

In the 1980s, the factory was one of the biggest air pollution sources in Lithuania (Table 2.7), emitting the larger part of all pollutants reported for Jonava. Along with the pollutants included in Table 2.7, emissions of chlorine have been occasionally

Table 2.7 Annual emissions (t) from all industrial enterprises at Jonava, Lithuania (1974–1989) and from the Achema plant (1980–2005)

Year	Dust	SO_2	CO	NO_x	NH_4
1974	7,300	11,000	25,600	–	–
1975	7,300	11,000	25,600	–	–
1978	4,800	7,500	19,600	2,200	2,420
1979	14,600	4,200	20,500	5,600	4,100
1980	16,400	5,400	28,100	6,400	5,100
	12,995[a]	3,901[a]	8,548[a]	4,148[a]	3,622[a]
1981	14,100	5,200	10,000	3,900	3,734[a]
	13,860[a]	4,630[a]	9,874[a]	3,862[a]	
1982	12,400	4,300	10,100	3,900	3,700
	11,476[a]	4,079[a]	10,541[a]	3,896[a]	3,633[a]
1983	7,300	4,400	10,400	4,500	3,720
	8,098[a]	3,699[a]	9,711[a]	3,595[a]	3,034[a]
1984	7,000	1,700	9,800	3,600	3,840
	6,328[a]	3,312[a]	9,928[a]	2,777[a]	2,591[a]
1985	7,400	1,600	9,800	3,000	3,870
	4,477[a]	2,635[a]	9,456[a]	2,886[a]	2,426[a]
1986	6,700	1,700	9,100	2,600	4,010
	3,238[a]	2,975[a]	10,291[a]	2,730[a]	2,559[a]
1987	5,500	3,000	9,400	2,500	2,495[a]
	1,705[a]	2,416[a]	9,682[a]	2,358[a]	
1988	4,300	2,300	8,700	2,400	1,551
	629[a]	1,991[a]	8,356[a]	2,206[a]	
1989	1,300	1,600	8,300	2,000	3,658
	271[a]	1,295[a]	6,608[a]	1,824[a]	
1990	305[a]	716[a]	6,143[a]	908[a]	2,249[a]
1991	351[a]	450[a]	7,318[a]	1,133[a]	2,249[a]
1992	246[a]	438[a]	6,904[a]	690[a]	2,055[a]
1993	212[a]	630[a]	3,924[a]	243[a]	678[a]
1994	274[a]	379[a]	3,013[a]	359[a]	720[a]
1995	292[a]	370[a]	3,475[a]	324[a]	1,287[a]
1996	285[a]	24[a]	3,450[a]	122[a]	645[a]
1997	265[a]	541[a]	3,510[a]	389[a]	382[a]
1998	203[a]	68[a]	5,704[a]	390[a]	257[a]
1999	301[a]	83[a]	5,362[a]	381[a]	197[a]
2000	323[a]	8[a]	5,770[a]	416[a]	286[a]
2001	–	50[b]	4,282[b]	430[b]	420[b]
2002	–	34[b]	4,192[b]	428[b]	446[b]
2003	–	24[b]	3,527[b]	478[b]	423[b]
2004	–	7[b]	3,639[b]	408[b]	416[b]
2005	–	0[b]	2,598[b]	514[b]	426[b]

Non-referenced values extracted from Emissions of Pollutants in Russia (1966–2006).
Other data sources:
[a] Juknys et al. (2003, Table 2.1; reprinted, in a modified form, with permission from Elsevier).
[b] Sujetovinė and Stakėnas (2007, and personal communication 2009).

reported (2,030 t in 1981, 1,561 t in 1984, 1,166 in 1987) (Emissions of pollutants in Russia 1966–2006). Small quantities of metals (Zn, Cu, Mn, Cr, Ni, Cd) detected in snow samples (Slavenene et al. 1987) presumably resulted from burning organic fuel.

Pollution Loads and the Extent of the Contaminated Territory

Ambient concentrations of pollutants in Jonava have been monitored since 1974; the peak reported values were 4.2 mg/m^3 of dust in 1975, 4.63 mg/m^3 of SO_2 in 1979, 0.34 mg/m^3 of NO_x in 1975, 0.70 mg/m^3 of HF in 1979, and 5.00 mg/m^3 of NH_4 in 1974–1975 (Emissions of pollutants in Russia 1966–2006).

In 1987–1989, annual depositions of sulphur and nitrogen in Jonava were 1,900 and 1,100 kg/km^2, respectively (Vasilenko et al. 1991). However, according to another data source (Armolaitis 1998), total (wet and dry) annual deposition of sulphur at a distance of 1–2 km from the factory in the mid-1980s comprised 5,000 kg/km^2 but was reduced to 1,500 kg/km^2 by the mid-1990s. To our knowledge, pollution loads have never been mapped; at the time of peak emissions (in the mid-1980s), the contaminated zone most likely ranged from 500 to 1,000 km^2.

Habitat Transformation due to Human Activity

Local forest damage was recognised in 1972 and has become extremely acute since 1979, when crown defoliation in conifers was recorded up to 10–12 km in the direction of prevailing winds, and complete dieback occurred within 2–3 km from the polluter (Juknys et al. 2003). By 1983, 20 km^2 of forest had been damaged by pollution (Dauskevicius 1984). Despite essential reduction of emissions (Table 2.7), at the end of the 1980s the forest damage expanded to 20–25 km in the direction of prevailing winds. Some signs of recovery appeared only in the 1990s (Juknys et al. 2003).

Brief History of Environmental Research

The studies of biotic effects caused by emissions of Achema are generally forestry-oriented, with detailed descriptions of the growth and vitality of Scots pine (Augustaitis 1989; Armolaitis 1998; Juknys et al. 2003) and fragmentary data on soil microbiota (Lebedeva & Lugauskas 1985), insect pests (Mastauskis 1987), and birds (Knistautas 1982, 1983).

Perception of the Environmental Situation

According to the web-based reports of the mass media, Achema was the first factory in Lithuania to adopt the EU requirement for an environmental management system, and was recently assessed as one of the top ten least polluting big chemical plants of the EU (E. Budrys, personal communication 2008).

2.2.2.5 Kandalaksha, Russia: Aluminium Smelter (Color Plates 15–17 in Appendix II)

Location and Environment

Kandalaksha is a small (population 38,100; data from 2007) town in the Murmansk Region, located on the Kola Peninsula on the coast of the Kandalaksha Gulf on the White Sea, 210 km south of Murmansk (Fig. 2.6). Originally, it was surrounded by mixed forests dominated either by Scots pine or, less frequently, by Norway spruce. Ground vegetation typically consisted of dwarf shrubs and green mosses (please see color plate 16 in Appendix II).

Pre-industrial History

Fishing has been the primary business of the local population for millennia. Although Kandalaksha has existed since eleventh century, only 806 inhabitants were recorded there in 1914. Town status was granted in 1938.

Industrial History

The industrial development of Kandalaksha started in 1915 with the building of the railway connecting St. Petersburg and Murmansk. The next important events were construction of the Niva hydropower station (completed in 1934) and the mechanical factory (launched in 1936). Building of the aluminium plant started in 1939 but was interrupted by World War II, and the smelter was only commissioned in 1951. Its main products are primary aluminium ingots, aluminium wire rod and billets. Annual production of aluminium in the late 1990s was 63,000 t (US Geological Survey 1999). During the period 2001–2007, the smelter employed 1,400 people and produced 70–75,000 t of aluminium annually (Boltramovich et al. 2003; www.rusal.ru).

Emissions Data

The aluminium smelter contributed 70–80% of all aerial emissions reported for the town of Kandalaksha in 1989–1991; in 1993–2000, its share declined to 53–64% (Emissions of pollutants in Russia 1966–2006), in particular due to ‘severe pressure from nature protection agencies, up to demand to reduce production of aluminium by 12%’ (Kruglyashov 2001). All emissions of both aluminium oxide (around 5,000 t in the mid-1990s; Evdokimova et al. 2007) and fluorine-containing substances (Table 2.8) originate from the smelter. In 2005, the new gas-cleaning system was put into operation, and a further decrease in emissions is expected in the coming years.

Table 2.8 Aerial emissions (t) from industrial enterprises at Kandalaksha, Russia

Year	Dust	SO_2	CO	NO_x	F-containing dust	HF
1970	–	–	–	–	–	>1,300
1971	–	–	3,100	–	–	1,300
1973	7,300	5,500	1,800	–	–	1,100
1974	7,300	5,500	1,800	–	–	1,100
1975	7,300	5,500	–	–	–	1,100
1978	20,100	5,500	8,300	–	–	1,425
1979	19,400	5,500	8,300	800	–	550
1980	20,100	4,200	7,600	300	–	790
1981	18,000	4,100	7,200	1,500	–	800
1982	23,200	3,700	7,300	300	–	800
1983	23,300	5,200	8,000	500	836	795
1984	23,700	6,600	8,900	200	833	790
1985	9,100	5,500	7,800	300	830	790
1986	8,600	5,200	7,000	200	824	800
1987	8,400	5,000	6,900	900	821	800
1988	8,100	4,700	6,800	200	816	784
1989	8,500	5,200	7,100	300	814[a]	780
			15,500[a]	600[a]		
1990	7,600	4,600	6,600	200	806	660
			8,800[a]	300[a]		775[a]
1991	5,244[b]	3,800	7,500	200	936	659[a]
	9,500		19,400[a]	1,400[a]		
1992	5,193[b]	–	–	–	–	–
1993	5,198[b]	5,800	9,300	600	848	705
	10.800					
1994	5,158[b]	8,700	11,300	800	–	694[b]
	9,400					848
1995	5,126[b]	4,800	7,800	340	–	693[b]
	8,900					848
1996	5,031[b]	5,300	8,100	300	–	688[b]
	9,000					839
1997	4,992[b]	5,100	8,500	300	–	688[b]
	9,700					839
1998	4,946[b]	5,700	8,700	300	–	687
	9,700					
1999	4,950[b]	5,800	8,200	300	–	686
	9,300					
2000	8,400	6,100	7,100	600	–	686
2001	8,400	6,200	7,300	600	–	672
2002	8,200	5,400	7,200	600	–	670
2003	5,400	5,400	7,100	600	–	383
2004	5,000	5,800	7,400	600	–	349
2005	3,800	6,000	6,700	500	–	274

Non-referenced values extracted from Emissions of Pollutants in Russia (1966–2006); emission of CO in 1983 corrected from the reported 800 to 8,000 t – the typing error presumed.
Other data sources:
[a] Kryuchkov (1993b).
[b] Kruglyashov (2001), data refer to the aluminium smelter only.

Pollution Loads and the Extent of the Contaminated Territory

Ambient concentrations of pollutants in Kandalaksha have been monitored since 1967; the peak reported values were 1.60 mg/m^3 of dust in 1967, 2.21 mg/m^3 of SO_2 in 1982, 0.43 mg/m^3 of NO_x in 1971, and 1.30 mg/m^3 of HF in 1970. Importantly, high concentrations of HF (0.30–0.50 mg/m^3) were recorded up to 2 km from the smelter in 1971–1973 (Emissions of pollutants in Russia 1966–2006).

A local increase in sulphate deposition from 1979–1983 was detected within approximately 300 km^2 (Kryuchkov & Makarova 1989). However, by the late 1980s–early 1990s, the sulphur-contaminated territories around major industrial centres of the Murmansk region had merged, and no local increase in sulphur deposition near Kandalaksha was detected in the 1990s (Kalabin 1999). In 1987–1989, annual depositions of sulphur and nitrogen in Kandalaksha were 1,000 and 300 kg/km^2, respectively (Vasilenko et al. 1991). The impact of the aluminium smelter on the local geochemistry in the mid-1990s was characterised as ‘surprisingly small’ (Reimann et al. 1998); however, emissions caused a substantial increase in the pH of both snow precipitation and forest litter (Evdokimova et al. 2005). The peak concentrations of fluorine in soils exceeded the regional background by a factor of 25–30 (Evdokimova et al. 2005).

During the period 1986–1991, a doubling of pollutant deposition (relative to the regional background) was recorded for 250 km^2 around Kandalaksha (Prokacheva et al. 1992). The content of fluorine in forest litter suggests that approximately 500 km^2 have been recently contaminated, with the severely contaminated zone (fluorine content increased by a factor of 6–25 relative to the regional background) limited to 2.5 km from the smelter (Evdokimova et al. 1997, 2007).

Habitat Transformation due to Human Activity

Severe damage to conifers and depression of field layer vegetation were apparent in the early 1980s, when Syroid (1987) classified the habitats next to the smelter as a zone of ‘complete destruction of ecosystems’, with 70–90% of soils void of vegetation. However, felling had been quite intensive around Kandalaksha until at least the 1970s; thus, initial deforestation near the smelter was most likely the result of clearcutting. Moreover, the presence of young Scots pines near the smelter (Syroid 1987) suggests that forest recovery was not prevented even at periods with the highest pollution pressure.

Kryuchkov and Makarova (1989, Fig. 18) claimed the presence of 25 km^2 of industrial barrens around the aluminium smelter at Kandalaksha; however, this information seems exaggerated. In particular, it contradicts the data by Georgievskij

(1990), who reported a decline of epiphytic lichens within 5 km^2 only. We repeatedly visited Kandalaksha in the early 1980s and observed Scots pine stands growing 1–3 km from the smelter (please see color plate 17 in Appendix II). We suggest that the acute environmental effects were local and mostly resulted from deposition of fluorine-containing dust in combination with other kinds of human-induced disturbances.

Visible forest damage in the early 1980s was observed within 450 km^2 (Syroid 1987); detectable lichen damage was reported within 1,300 km^2 (Georgievskij 1990).

Brief History of Environmental Research

The first reports of the environmental situation around Kandalaksha (Syroid 1987; Georgievskij 1990) were narrative and contained neither numerical estimates of the effects nor statistical analysis. Quantitative information is available only for soil micromycetes (Evdokimova et al. 1997, 2007) and several groups of soil invertebrates (Zainagutdinova 2003). An integrated environmental study (Evdokimova et al. 2005) produced mostly inconclusive results due to methodological flaws, including a poorly replicated sampling design, selective reporting of information (e.g., data on individual taxa of soil mesofauna are given for the most polluted site, but data for the control site are missing), and an absence of proper statistical support for the majority of the conclusions. In particular, the contrast between one polluted and one unpolluted site (e.g., Evdokimova et al. 2007) does not allow to attribute the detected differences to the impact of pollution. Our team recently published information on growth of three species of herbs (Kozlov & Zvereva 2007b) and phenology of mountain birch (Kozlov et al. 2007) in the impact zone of the smelter at Kandalaksha.

Perception of the Environmental Situation

Recent publications in mass media indicate that the situation in this town is reasonably good in comparison to other towns of the Murmansk Region, and suggest that the existing sanitary zone around the smelter (it is now 1 km wide) is too large (Anonymous 2007).

2.2.2.6 Karabash, Russia: Copper Smelter (Color Plates 18–23 in Appendix II)

Location and Environment

Karabash (population 15,400; data from 2007) is an industrial town of the Chelyabinsk Region, located on the eastern slopes of the South Ural Mountains 90 km northwest of Chelyabinsk (Fig. 2.7). The town lies within a flat-bottomed valley, roughly parallel to the prevailing wind direction and surrounded by hills (please see color plate 21 in Appendix II) having an altitude up to 610 m. This valley was originally covered by south taiga forests formed by Scots pine and common birch, with well-developed herbaceous vegetation (please see color plate 19 in Appendix II).

Pre-industrial History

The region has hosted mining and metal production for over 3,000 years. The settlement Sak-Elginskij (later renamed Soimanovskij) was founded in 1822 close to the current location of Karabash by gold-miners; in the early 1900s, the population was around 400.

Industrial History

For unknown reasons, many publications have reported contradictory dates for the most important events in the industrial history, including in particular the opening of a concentrating mill and a period of temporary closure of the smelter. All the dates below follow the book by Novoselov (2002).

The building of the first copper smelter started in 1834 at Sak-Elginskij; from 1837 to 1842, it produced 22 t of copper from local ores, and it was then developed into an iron factory. The second copper smelter was launched at another locality in 1907 and operated for 3 years. The third smelter was built in 1910, again at a new site (approximately between the two earlier works), and the settlement grew around it. This smelter utilised modern technology to produce blister copper, and by 1915, one third of the Russian copper output originated from Karabash. Copper production from 1907 to 1918 totalled 56,000 t.

Both mining and smelting operations were discontinued between 1918 and 1925. In 1930, a concentrating mill was built in the eastern part of the settlement. Town status was granted in 1933. Copper production in 1940 reached 22,000 t but declined during the World War II to 6,750 t in 1945 due to a shortage of electricity and workforce. The peak population of 50,000 occurred between the late 1950s and the 1960s, when mining, ore beneficiation and smelting operations were at their peaks.

In 1987, Soviet authorities decided to modify the smelter for recycling of non-ferrous metals. The concentrating mill and one of the copper furnaces were closed in November 1989. Closures occurred gradually until 1997, when the smelting operations were discontinued totally. The ownership of the plant and of the nearby mine changed in 1998, and a new enterprise, 'Karabashmed' (with 1,400 employees), was launched using the existing facilities. Annual copper production reached 30,000 t in 2000 and further increased to 40,000 t in the mid-2000s. Since 2005, the plant has also produced sulphuric acid (31,600 t from May to December of 2005).

Emissions Data

The emissions history of the smelter is well documented (Table 2.9), although official data (Emissions of pollutants in Russia 1966–2006) have only been available since 1984. During the period 1989–2003, the smelter contributed 98.3–99.9% of all emissions at Karabash (Emissions of pollutants in Russia 1966–2006). It is expected that ongoing modernisation will reduce the annual emissions of sulphur dioxide to less than 5,000 t (www.karmed.ru).

Table 2.9 Aerial emissions (t) from industrial enterprises at Karabash, Russia

Year	Dust	SO_2	CO	NO_x	Cu	Pb	Zn	As
1956	–	–	–	–	540[a]	1,760[a]	1,940[a]	–
1957	–	–	–	–	410[a]	990[a]	1,660[a]	–
1958	12,100[a]	–	–	–	540[a]	1,280[a]	1,830[a]	–
1959	–	–	–	–	1,030[a]	1,060[a]	2,130[a]	–
1960	20,400[a]	–	–	–	1,100[a]	1,300[a]	3,290[a]	1,900[b]
1961	23,800[a]	–	–	–	1,200[a]	2,250[a]	4,020[a]	–
1962	10,600[a]	–	–	–	1,780[a]	1,790[a]	3,560[a]	–
1965	29,400[a]	–	–	–	1,600[a]	2,300[a]	3,820[a]	1,610[a]
1966	25,600[a]	–	–	–	1,350[a]	1,990[a]	3,410[a]	1,850[a]
1967	28,600[a]	–	–	–	1,340[a]	2,880[a]	4,410[a]	2,070[a]
1968	31,700[a]	–	–	–	1,360[a]	3,280[a]	5,370[a]	2,420[a]
1969	29,900[a]	–	–	–	1,440[a]	3,820[a]	5,140[a]	2,600[a]
1970	28,800[a]	364,500[a]	–	–	1,530[a]	2,570[a]	4,550[a]	1,920[a]
1971	25,800[a]	281,200[a]	–	–	1,250[a]	3,350[a]	4,680[a]	1,680[a]
1972	18,700[a]	–	–	–	830[a]	3,110[a]	3,150[a]	1,070[a]
1973	27,900[a]	273,100[a]	–	–	860[a]	3,300[a]	3,430[a]	1,720[a]
1974	27,400[a]	259,800[a]	–	–	740[a]	2,870[a]	3,470[a]	1,480[a]
1975	27,100[a]	252,000[a]	–	–	600[a]	2,720[a]	2,960[a]	1,380[a]
1976	25,900[a]	233,800[a]	–	–	1,070[a]	3,400[a]	4,740[a]	2,300[a]
1977	29,000[a]	267,200[a]	–	–	1,370[a]	3,930[a]	5,140[a]	2,400[a]
1978	26,000[a]	181,100[a]	–	–	–	3,410[a]	–	1,870[a]
1979	23,900[a]	183,700[a]	–	–	–	3,760[a]	–	2,330[a]
1980	20,300[a]	184,000[a]	–	–	1,140[a]	3,160[a]	4,100[b]	1,990[a]
1984	23,600	137,300	–	100	1,600	2,532	3,200	1,803
1985	23,300	153,500	–	100	1,400	2,130	3,300	1,700
1986	21,300	153,000	–	100	1,200	1,960	3,000	1,670
1987	18,700	148,100	–	100	1,300	1,650	2,600	1,300
1988	20,500	142,500	–	100	–	–	–	–
1989	20,500	142,500	–	100	–	483	–	–
1990	3,400	46,900	500	–	435	254	1,363[b]	75
	3,900[b]				485[b]			
1991	2,200	6,000	100	100	88	119	–	31
1994	200[b]	600[b]	–	–	21[b]	9[b]	63[b]	4[b]
1996	200	40	200	100	–	–	–	–
1997	1,200[b]	4,500[b]	–	–	100[b]	30[b]	200[b]	20[b]
1998	200	5,000	200	100	6	3	–	–
2000	10,100	79,000	15,800	400	–	72	–	99
2001	13,800	71,900	12,200	300	–	92	–	110
2002	14,800	67,700	14,800	400	–	63	–	83
2003	–	–	–	–	340[c]	–	–	–
2004	2,300	66,300	800	100	–	26	–	7
2005	1,300	38,100	1,600	90	–	20	–	7

Non-referenced values were extracted from Emissions of Pollutants in Russia (1966–2006); note that data for the years 1993–1995, 1997, 1999 and 2003 have not been reported in these publications. Other data sources:

[a] Stepanov et al. (1992).

[b] Chernenkova et al. (2001).

[c] E. Vorobeichik (personal communication, 2008).

Pollution Loads and the Extent of the Contaminated Territory

Ambient concentrations of pollutants in Karabash have been monitored since 1972; the peak reported values were 4.00 mg/m^3 of dust in 1973 and 6.20 mg/m^3 of SO_2 in 1974 (Emissions of pollutants in Russia 1966–2006). The peak ambient SO_2 level in 2000 (i.e., after reopening the smelter) reached 20 mg/m^3 at a 1 km distance from the smokestack (Udachin et al. 2003). A detailed investigation of total airborne suspended particulates performed in 2000–2001 demonstrated that a large (83–100%) fraction was respirable; these particulates contain high levels of potentially toxic metals and are thought to pose a severe risk to human health (Williamson et al. 2004).

From 1987 to 1989, annual depositions of sulphur and nitrogen in Karabash were 16,200 and 1,100 kg/km^2, respectively (Vasilenko et al. 1991). In the early 1990s, deposition of heavy metals near the smelter exceeded the regional background by a factor of 45 for copper, 20 for lead, and 5 for cadmium (Bolshakov et al. 2001). In 1981, soils near the smelter contained 2,500 mg/kg of copper and 1,000 mg/kg of zinc (Chernenkova 1986); later, a peak value of 6,744 mg/kg of copper in forest litter was recorded 3 km northwest of the polluter (Stepanov et al. 1992). The peak concentrations of other elements in soils of the industrial barrens were 10,000 mg/kg of zinc, 3,000 mg/kg of lead, and 1,500 mg/kg of arsenic (Makunina 2002). In the mid-1990s, copper concentrations in soils exceeded the background level by a factor of 128 or more for 5.5 km^2 (Nesterenko 1997).

During the period 1986–1991, a doubling of pollutant deposition (relative to the regional background) was recorded for 250 km^2 around Karabash (Prokacheva et al. 1992). In 1998, depositions of arsenic and copper reached the regional background levels between 30 and 40 km from the smelter (Frontasyeva et al. 2004). Metal accumulation in lichens demonstrated a similar extent of the contaminated territory (Purvis et al. 2004). Thus, although the distribution of pollutants has not been properly mapped, we estimate that emissions from the Karabash smelter have contaminated 3–4,000 km^2.

Habitat Transformation due to Human Activity

The occurrence of industrial barrens around Karabash is well documented (Stepanov et al. 1992; Kozlov & Zvereva 2007a). Development of the barrens presumably started in the 1940s, following intensive felling near the town of Karabash. Clearcutting continued until the 1950s, leaving no stands within 5 km of the smelter (Stepanov et al. 1992). The barren sites (please see color plates 20, 21 and 23 in Appendix II) are now surrounded by semi-barren landscapes – birch forests with missing field layer vegetation (please see color plate 22 in Appendix II). The absence of birch seedlings in these stands suggests that their state is transient; these birch forests will likely turn into industrial barrens following either fire or felling (Kozlov & Zvereva 2007a), or when birches will reach their upper age limit (Zverev 2009). In 1983, dead and declining stands occupied 80 km^2, surrounded by 210 km^2 of damaged forests; in 1992, these areas were 35 and 160 km^2, respectively (Butusov et al. 1998). These data are in line with the conclusions of Chernenkova et al. (1989) that birch forests located 10–12 km from the polluter were not modified by pollution.

Brief History of Environmental Research

Research on pollution impacts of the Karabash smelter started in the early 1980s, when a team from the Severtsev Institute of Evolutionary Morphology and Ecology of Animals (Moscow) collected data on the contamination of soils, water, and plants, as well as on the composition and productivity of plant communities (Chernenkova 1986). This team continued an integrated monitoring (with an emphasis on vegetation) until the mid-1990s (Chernenkova et al. 1999; Chernenkova 2002), involving remote sensing data for outlining the extent of pollution damage (Bugrovskii et al. 1985; Butusov et al. 1998). The results have been summarised in two monographs (Stepanov et al. 1992; Chernenkova 2002). Unfortunately, T. Chernenkova and her colleagues published many of their data sets and conclusions repeatedly. An absence of cross-references and missing sampling dates in these publications create numerous problems for using these data in meta-analyses.

Although published data are diverse, changes in plant growth and community structure were much better documented than the effects of pollution on animals. Several data sources (Stepanov et al. 1992, and references therein; Kucherov & Muldashev 2003) reported a decline in the growth of Scots pine, as well as an absence of changes in the radial increment of common birch; however, non-replicated (or poorly replicated) study designs and an absence of statistical analyses diminish the value of this information. Changes in species richness and biomass (i.e., productivity) were reported for soil microbiota (Mukatanov & Shigapov 1997), soil algae (Stepanov et al. 1992), epiphytic lichens (Williamson et al. 2004), vascular plants (Chernenkova et al. 1989), and soil macrofauna (Nekrasova 1993). Studies of vertebrates seem to be restricted to short reports on changes in vole reproduction (Lukyanova 1987; Chernousova 1990) and information on the absence of small mammals in the most polluted habitats (Stepanov et al. 1992).

A decrease in emissions due to the closure of the plant in the 1990s resulted in a slight improvement of the environmental situation. The initial stages of the recovery of field layer vegetation were observed in slightly to moderately polluted forests (5–9 km from the smelter), while the state of the most polluted forests (3 km northeast of the smelter) did not change (Chernenkova et al. 1999). Later on, grasses started to colonise barren, heavily eroded slopes of the Zolotaya Mountain next to the smelter (Chernenkova et al. 2001), and the radial increment of Scots pine increased near the polluter (Kucherov & Muldashev 2003).

Perception of the Environmental Situation

In 1992, the United Nations Environmental Programme designated Karabash as one of the world's most polluted towns (Anonymous 1999). Newspaper's descriptions of Karabash resemble apocalyptic nightmares: 'The sky turned black.

The snow became black. The withered branches of ailing trees got a new coating of black' (Filipov 2004). The mountains near Karabash are called 'bald' by the locals, as their slopes are almost void of vegetation. The other end of town looks like a lunar landscape, with nothing but dust for hundreds of metres (Anonymous 1999). A plan to hold a referendum on shutting down the smelter faltered after unidentified assailants badly beat one of the initiators (Filipov 2004).

Karabash was visited by a team from the Blacksmith Institute in February of 2005. The adverse health effects caused by the smelter were partly acknowledged by local health and municipal authorities. The priorities here are relocating people living in the buffer zone elsewhere and installation of pollution control devices in the smelter (www.pollutedplaces.org).

Intriguingly, in 2005 the smelter at Karabash was awarded a medal 'For achievements in nature protection'. At the ceremony held in the Kremlin, Moscow, it was announced that 'already now, Karabash can be removed from the list of ecologically unfavourable localities' (www.elisprom.ru). However, this conclusion seems premature, since in 2007 we have not observed an improvement of the polluted landscapes around Karabash (please see color plates 18–23 in Appendix II).

2.2.2.7 Kostomuksha, Russia: Iron Pellet Plant (Color Plates 24–26 in Appendix II)

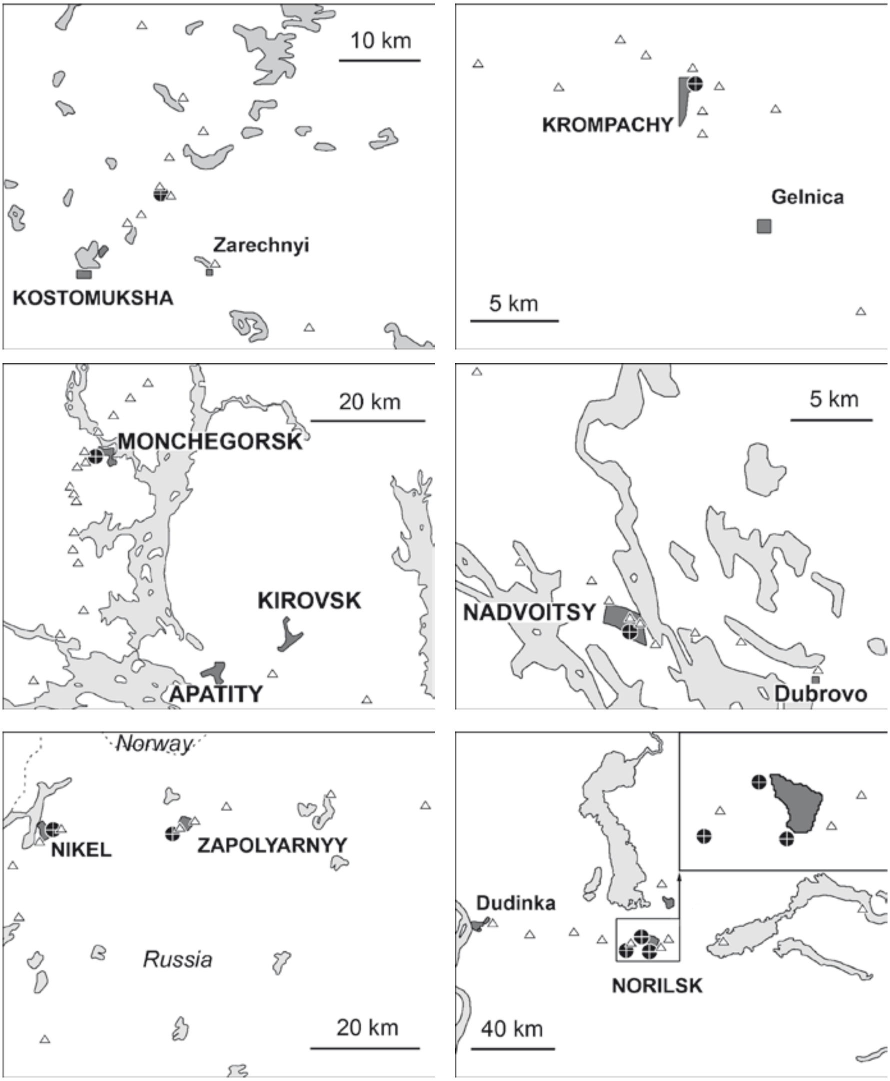
Location and Environment

Kostomuksha (population 30,000; data from 2007) is a newly built town. It was established in 1977 as an urban-type settlement and populated by people from various regions of the Soviet Union; town status was granted in 1983. Kostomuksha is located in the north-western part of the Republic of Karelia on the shore of Kontoki Lake, 40 km from the border with Finland (Fig. 2.8).

In the mid-1970s, two thirds of the territory surrounding Kostomuksha was covered by forest, and about one-quarter by bogs. Some stands were still in an almost virgin state, representing old-growth mid-taiga forests dominated by Scots pine or Norway spruce, with a ground layer formed by dwarf shrubs and green mosses (please see color plate 25 in Appendix II).

Pre-industrial History

Kostomuksha area is best known for poems of the Finnish epos 'Kalevala'. When Elias Lönnrot visited Kostomuksha in 1837 to record this epos, the village had only ten houses. Before the Winter War (1939), Kostomuksha (or Kostamus) belonged to the sparsely populated Finnish municipality of Kontokki, with 1,872 inhabitants in 1907. During the war, the village was ruined, and in 1948, only five persons who were capable of working, a few horses, a cow and a sheep were living in Kostomuksha. By the late 1950s, Kostamuksha had become unpopulated, and only a few people were still living in the entire area.



Figs. 2.8–2.13 Distribution of study sites (triangles) around investigated polluters (black circles with white cross inside). Names of larger settlements (usually towns) are capitalised. **2.8**, iron pellet plant in Kostomuksha, Russia; **2.9**, copper smelter in Krompachy, Slovakia; **2.10**, nickel-copper smelter in Monchegorsk, Russia; **2.11**, aluminium smelter in Nadvoitsy, Russia; **2.12**, nickel-copper smelter in Nikel, and ore-roasting factory in Zapolyarnyy, Russia **2.13**, nickel-copper smelters in Norilsk, Russia

The presence of iron ores around Kostomuksha has been known for a long time, at least since the beginning of the nineteenth century. In the 1850s, some local inhabitants dug mud from Kostamus Lake, smelted it and made axes and other iron items. Intensive geological exploration of this region started in 1946.

Industrial History

The decision to build the Kostomuksha ore mining and processing enterprise was made in 1969, and a contract with Finnish companies that conducted a substantial part of the work was signed in 1977. Mining of depleted ferruginous quartzite began in 1978, and production of iron-ore pellets (high-grade metallurgical stock) was launched in 1982. Development continued until 1985, when the full capacity had been achieved. In 1993, the enterprise was reorganised into an open joint-stock company, Karelsky Okatysh, which is the principal employer (8,600 persons in 2001) of the town (okatysh.home.spb.ru). In 2004, the company mined 22,320,000 t of ore and produced 7,584,000 t of iron pellets (ru.wikipedia.org).

Emissions Data

Karelsky Okatysh contributed 99.4–99.8% to the total emissions of pollutants at Kostomuksha (Emissions of pollutants in Russia 1966–2006). Only the amounts of gaseous pollutants have been reported (Table 2.10); no data are available on emissions of either metals (with dust) or organic pollutants. However, metal emissions can be roughly estimated from the amount of dust using concentrations reported by Shiltsova and Lastochkina (2004); 6,900 t of dust (emitted in 2000) is likely to contain approximately 350 t of iron, approximately 27 t of zinc, and approximately 0.6 t of copper.

Table 2.10 Aerial emissions (t) from industrial enterprises at Kostomuksha, Russia

Year	Dust	SO_2	CO	NO_x
1987	5,400	61,300	400	2,500
1988	5,100	61,900	400	2,700
1989	4,800	62,500	400	2,700
1990	4,700	62,200	2,200	3,400
1991	5,200	54,700	600	2,500
1992	6,000[a]	60,400[a]	1,300[a]	2,200[a]
1993	5,300	53,100	600	1,600
1994	6,400	48,100	600	1,500
1995	5,000	44,600	600	1,300
1996	6,400	47,400	500	1,200
1997	6,000	32,200	900	1,500
1998	6,400	37,700	900	1,600
1999	6,900	34,400	1,000	1,300
2000	6,900	30,200	1,100	1,300
2001	6,500	30,000	1,200	1,400
2002	6,400	32,700	1,300	1,400
2003	6,600	33,500	1,300	1,400
2004	6,400	35,400	1,200	1,400
2005	6,100	36,500	1,400	2,100

Non-referenced values extracted from Emissions of Pollutants in Russia (1966–2006).
Other data sources:
[a] Krutov et al. (1998).

Pollution Loads and the Extent of the Contaminated Territory

During the mid-1990s, sulphur deposition within 2–3 km from the plant was 2,100 kg/km^2, i.e., nearly ten times as high as the regional background of 260 kg/km^2 (Shiltsova & Lastochkina 2004). In 1986–1987, the extent of the most contaminated zone (with an approximately 100-fold increase in dust deposition) was 4–5 km, and the extent of the moderately contaminated zone (with an approximately 10–30-fold increase in dust deposition) was 25–30 km (Lazareva et al. 1988). Monitoring of wet precipitation from 1992 to 1994 indicated that to the west of the smelter (nearly opposite the direction of prevailing winds), emissions extend to about 30–40 km. However, a substantial (tenfold) increase in annual deposition of iron was only detected within 5 km, while the deposition at localities 22–38 km from the polluter was only 1.5 times as high as at more distant (63–114 km) plots (Poikolainen & Lippo 1995). The iron content in soils near the polluter in the late 1990s–early 2000s exceeded the regional background by a factor of 60 (Opekunova & Arestova 2005). Levels of Li, B, Al, Fe, Ni, Cu, Zn, Hg, Mn, and Mo, as well as hydrocarbons, phthalates and phenols in snow samples collected near the polluter in 2001, were found to exceed the maximum allowable concentrations (Lebedev et al. 2003). High concentrations of calcium-containing dust in aerial emissions resulted in increased pH values of precipitation near the factory (Potapova & Markkanen 2003). However, at distances exceeding 2 km, a slight acidification of forest litter was detected after 6 years of pollution impact (Lazareva et al. 1988).

During the period 1986–1991, a doubling of pollutant deposition (relative to the regional background) was recorded for 390 km^2 around Kostomuksha (Prokacheva et al. 1992). However, mapping of the entire territory of Karelia for sulphur and metal contamination in the mid-1990s revealed increases in sulphur and iron content in mosses (by a factor of 2 or more) for approximately 10.1 and 12.9 km^2 near Kostomuksha, respectively (Fedorets et al. 1998). On the other hand, the extent of the territory contaminated by manganese, chromium and vanadium was recently estimated as approximately 1,200 km^2 (Gulyaeva & Kalieva 2004).

Habitat Transformation due to Human Activity

Three years of pollution impact appeared sufficient to enhance accumulation of forest litter and reduce the biomass of mosses and field layer vegetation near the factory (Chernenkova 1991). The appearance of dust on plants and litter in the immediate vicinity of the factory, a partial replacement of dwarf shrubs by herbaceous vegetation, and a decline of epiphytic lichens are directly attributable to pollution (please see color plate 26 in Appendix II). However, Scots pine stands at distances exceeding 5 km showed no signs of pollution damage, and no effects on growth of Scots pine had been detected until very recently (Krutov et al. 1998; Sinkevich 2001).

Brief History of Environmental Research

Environmental and ecological research conducted from 1972 to 1975, i.e., several years prior to launching the factory, provided detailed information on the pre-industrial state of many components of the terrestrial and aquatic ecosystems (Biske et al. 1977). Since the launch, environmental monitoring has continued almost uninterrupted until very recently, providing a unique opportunity to follow environmental changes during the first years of pollution impact. The largest body of information is collected on pollution-induced changes in soil quality and microbial activity (Zaguralskaya 1997; Germanova & Medvedeva 2001), soil nematoda (Matveeva et al. 2001), epiphytic lichens (Fadeeva 1999), growth, physiology and vitality of Scots pine (Fuksman et al. 1997; Kaibiyainen et al. 2001; Lamppu & Huttunen 2003; Sazonova et al. 2005), and on the structure and productivity of plant communities (Chernenkova 1991, 2002). Since researchers from the Forest Institute at Petrozavodsk tend to publish the same results repeatedly, less than half of the data sources available to us (Table 2.3) contain original information.

Perception of the Environmental Situation

Due to the proximity to the Finnish border, emissions from Kostomuksha soon became an international concern. Several research projects established in the early 1990s concluded that the effects of contamination on the Finnish environment and population are relatively minor (Lumme et al. 1997), and the recent report by the Finnish Ministry of the Environment (Ympäristöministeriö 2007) says that there are no ‘direct, continuous, significant environmental threats’ to the Finnish environment from the Karelian side.

2.2.2.8 Krompachy, Slovakia: Copper Smelter (Color Plates 27–29 in Appendix II)

Location and Environment

Krompachy (population 8,800; data from 2001) is a town in Slovakia, situated in the central Spiš region, in the valley of the Hornád River, surrounded by three mountain ranges with summits 900–1,100 m above sea level (Fig. 2.9). Norway spruce is the prevailing tree in coniferous and mixed forests between 400 and 800 m above sea level (please see color plate 28 in Appendix II). At lower altitudes, the forests are mostly composed of European beech (*Fagus sylvatica*) with contributions of Silver fir (*Abies alba*), Norway spruce, and common birch.

Pre-industrial History

Metallurgy ranks among the most ancient industries within the territory of Slovakia; local polymetallic ores have been exploited since the Bronze Age. Iron and non-ferrous (copper- and silver-containing) ores have been mined and processed in the area surrounding Krompachy for about 700 years. The first written record of the existence of the settlement is dated 1282, and the town of Krompachy was founded in the mid-fourteenth century.

Industrial History

During the nineteenth century, the Krompachy Iron Mining Company was gradually formed from smaller iron-mills; iron and copper rolling mills were also built. In the early 1900s, the Krompachy Ironworks, with 3,500 employees (of 6,500 inhabitants of the town), produced 85,000 t of iron annually and was the biggest ironworks of the former Hungary. It was closed after World War I. Production of copper started in 1843. A copperworks built in 1937 on the site of the old ironworks produced 1,500 t of copper annually and operated until early 1945, when it was destroyed by the withdrawing German troops. The present smelter was launched in 1951 for processing ore concentrates and recycled copper materials, with an annual capacity of 20,000 t of copper; 29,000 t was produced in 1995 and 25,000 in both 1996 and 1997. For a long time Krompachy was a flourishing town; however, production was ceased in 1999 due to falling world copper prices, and 1,000 workers were dismissed. The smelter was reopened in September 2000 by the newly established joint-stock company, Kovohuty (Barecz 2000). The town of Krompachy also houses several other industries, including production of alloys, electronic goods, and electromechanical equipment for both industrial and domestic use.

Emissions Data

While emissions of sulphur dioxide are more or less properly documented (Table 2.11), data on metal emissions are scarce. The composition of dust arising from different technological processes was reported by Hronec (1996); however, contributions of these processes to the total amount of emitted dust remain unknown. Occasional information suggests that annual copper emissions in the 1990s were between 40 and 55 t, lead emissions decreased during the first half of the 1990s from 50 to 20 t (Kalač et al. 1996), and arsenic emissions in 1986 were as high as 90 t (Andersen 2000).

Pollution Loads and the Extent of the Contaminated Territory

The highest reported concentrations of metals in soil are 8,437 mg/kg of copper, 1,482 mg/kg of zinc, and 3,343 mg/kg of lead (Maňkovská 1984; Banásová & Lackovičová 2004); the regional background levels are reached at 7–12 km from the smelter (Wilcke et al. 1999). Soil acidification was only detected within 3–5 km from the smelter (Hronec 1996; Wilcke et al. 1999). Importantly, a decrease in emissions in early the 1990s did not result in lower metal contamination of edible mushrooms, and concentrations of Hg, Cd, Pb and Cu in many samples collected 3–5 km east of the smelter exceeded the statutory limits (Svoboda et al. 2000).

Maňkovská (1984) outlined three zones of environmental contamination around Krompachy. The first zone, with pollutant concentrations exceeding the regional background by a factor of 150 or more, covered 28.4 km^2; the second zone (pollution loads 6 to 150 times higher than the background) covered 44.7 km^2. The borders of the third, less contaminated zone, were incompletely shown on the map by Maňkovská (1984), but its area still exceeded 150 km^2.

Table 2.11 Aerial emissions (t) from copper smelter at Krompachy, Slovakia

Year	SO_2	NO_x	Dust
1952	5,600	–	11,900
1955	6,800	–	12,220
1960	7,400	–	12,670
1965	7,032	–	10,096
1971	3,040	–	1,387
1975	15,616	–	1,086
1980	19,654	–	1,869
1985	24,341	–	1,724
1986	20,000[a]	–	1,400[a]
1989	13,700[b]	–	–
1990	23,000	–	1,100
1992	10,156	–	73
1995	5,348[b]	43[b]	86[b]
1996	10,187[c] 9,008[d]	90[d]	188[c]
1997	7,236[d]	99[d]	296[e]
1998	2,543[e]	98[e]	151[e]
2002	0.5[f]	20[f]	3.3[f]

Non-referenced values were extracted from Hronec (1996, Table 2.8).
Other data sources:
[a] Andersen (2000).
[b] Lackovičová et al. (1994).
[c] Slovak Environmental Agency (1997).
[d] Slovak Environmental Agency (1998).
[e] Maňkovská (2003).
[f] Ministry of the Environment of the Slovak Republic (2004).

Habitat Transformation due to Human Activity

Development of the industrial barrens presumably began in the 1980s, and recently they covered less than 0.5 km^2. Extensive soil erosion (please see color plates 27 and 29 in Appendix II) occurs on the north-facing slope of a hill adjacent to the smelter (Maňkovská 1984; Banásová & Lackovičová 2004; Kozlov & Zvereva 2007a). Although Krompachy is surrounded by a 'lichen desert' (Lackovičová 1995), a rare lichen species, *Cladonia rei* Schaer, is abundant on bare, acid soils near the smelter (Hajdúk & Lisiká 1999).

Brief History of Environmental Research

Information on the environmental effects caused by aerial emissions of the Krompachy smelter is scarce, with contamination patterns documented much better than the biotic effects of pollution. Data on soil pH, as well as concentrations of both macronutrients and pollutants, were published by Hronec (1996) and Wilcke et al. (1999). Deposition of metals with dust was measured at 15 sites between Krompachy and Košice in 1999 (Bobro et al. 2000). The effects of emissions on vegetation were first explored by Kaleta (1982). A detailed description of field layer vegetation at the most polluted, nearly barren, site was provided by Banásová and Lackovičová (2004). Data on animals are restricted to reports on soil nematodes (Sabová & Valocká 1996).

2.2.2.9 Monchegorsk, Russia: Nickel-Copper Smelter (Color Plates 30–39 in Appendix II)

Location and Environment

Monchegorsk (population 49,400; data from 2007) is an industrial town in the Murmansk Region, located 115 km south of Murmansk, between Imandra Lake and the Monche-tundra mountain ridge (reaching 965 m above sea level) (Fig. 2.10). Monchegorsk is only 150 km south of the tree line formed by mountain birch; up to the mid–1930s, virgin Scots pine stands and an impenetrable Norway spruce forest with beards of epiphytic lichens covered the area close to the recent position of Monchegorsk (Bobrova & Kachurin 1936).

Pre-industrial History

Although the Kola Peninsula has been populated since approximately 6000 BC, in 1913 there were only 13,200 inhabitants, mostly in seashore settlements. Until the railway was built in 1916, central parts of the Kola Peninsula were accessible only by foot or by boat. Descriptions of the landscape and vegetation made in the 1920s–1930s reflect a virgin nature, slightly affected by traditional forms of land use such as reindeer herding, fishing and hunting (Kozlov & Barcan 2000).

The discovery of apatite ores in the Khibiny Mountains (1920–1926) and of nickel-copper ores in the Monche-tundra (1929–1932), followed by the decision of the Soviet government to develop mining and ore processing factories in the central part of the Kola Peninsula (1929–1935), resulted in rapid changes. The Severonikel smelter and the town of Monchegorsk were built in the mid-1930s on a previously unpopulated territory using forced labour. The population of the Monchegorsk area grew from a single Saami family in 1930 to 200 persons in 1933 and 34,190 persons in 1938, and town status was granted to Monchegorsk in 1937. Intensive development of the town required the clear-cutting of large forest areas, and the rapid population growth resulted in a drastic increase in forest fires.

Industrial History

Construction of the smelter started in 1934, and it was officially opened in 1937. Operations were discontinued the week after the German attack on the USSR in 1941. The equipment was partially sent to Norilsk, where it served as the basis for the recently operating nickel smelter; another portion of the equipment was moved to Orsk.

Restoration of the factory started in 1942, the mine was restored in 1943, and nickel production began before the end of World War II. However, regular operations started only in 1946–1947 with ores from the local Nittis-Kumuzhje deposit, which was exhausted in 1977. Later, sinter-roasted ores from Zapolyarnyy and both ores and nickel matte from Norilsk (since 1968) were processed. Recently, the smelter has used a breakage, waste products and raw material from both domestic and foreign suppliers.

The smelter had no air-cleaning facilities until 1968, when production of sulphuric acid was launched to utilise converter and roaster gases. The second line of sulphuric acid production was installed in 1979. The last substantial expansion of the smelter took place in the 1980s. One of the most polluting smelting departments was closed in 1998, due to both economic and ecological reasons (Pozniakov 1993, 1999; Alexeyev 1993; Barcan 2002b).

Until 1950, nickel and copper production did not exceed 10,000 and 6,300 t, respectively. In the 1980s, annual production reached 140,000 t of nickel and 100–120,000 t of copper (Pozniakov 1993). Production decreased in the 1990s, but it increased in the 2000s to 100–122,000 t of nickel and 74–106,000 t of copper. Other products include concentrates of precious metals and sulphuric acid (www.nornik.ru). Between 2002 and 2007, the number of employees decreased from 16,601 to 11,374.

Emissions Data

During the first years of smelting, losses were as high as 10–15% of the metal content of the ores, which, in combination with the data on metal production and on sulphur content in ores, allows us to estimate annual emissions for the late 1940s as 60,000 t of sulphur dioxide, 1,000–1,500 t of nickel and 500–1,000 t of copper (Kozlov & Barcan 2000). During the period 1989–1999, the smelter produced 99.6–99.9% of all aerial emissions reported from the town of Monchegorsk (Table 2.12). Along with the pollutants included in this table, emissions of H_2SO_4 (255 t in 1979, 170 t in 1987) and chlorine (438 t in 1987) have been occasionally reported (Emissions of pollutants in Russia 1966–2006). Both the nature and origin of emissions of the smelter at Monchegorsk are described in details by Barcan (2002b), a professional chemist who worked at this smelter for many years. Recently, Boyd et al. (2009) estimated emissions of As, Cd, Cr, Pb, Sb, V and Zn on the basis of ore chemistry and annual production data.

Pollution Loads and the Extent of the Contaminated Territory

Ambient concentrations of pollutants in Monchegorsk have been monitored since 1967; the peak reported values were 2.90 mg/m^3 of dust in 1970, 6.84 mg/m^3 of SO_2 in 1973, and 1.12 mg/m^3 of NO_x in 1967 (Emissions of pollutants in Russia 1966–2006). In 1987–1989, annual depositions of sulphur and nitrogen in Monchegorsk were 2,100 and 400 kg/km^2, respectively (Vasilenko et al. 1991). The long-term emissions

Table 2.12 Aerial emissions (t) from industrial enterprises at Monchegorsk, Russia

Year	Dust	SO_2	CO	NO_x	Ni	Cu	Co
1960	–	134,000[a]	–	–	–	–	–
1961	–	139,000[a]	–	–	–	–	–
1962	–	136,000[a]	–	–	–	–	–
1963	–	147,000[a]	–	–	–	–	–
1964	–	148,000[a]	–	–	–	–	–
1965	–	200,000[a]	–	–	–	–	–
1966	–	191,000[a]	–	–	–	–	–
1967	–	199,000[a]	–	–	–	–	–
1968	–	76,400[a]	–	–	–	–	–
1969	–	94,000[b]	–	–	–	–	–
1970	–	101,000[b]	–	–	–	–	–
1971	–	117,200	–	–	–	–	–
1972	–	117,200	–	–	–	–	–
1973	7,300	138,700	–	–	–	–	–
		215,000[b]					
1974	7,300	138,700	–	–	–	–	–
		259,000[b]					
1975	9,100	259,200	–	–	–	–	–
1976	–	268,000[b]	–	–	–	–	–
		307,100[c]					
1977	–	253,000[c]	–	–	–	–	–
1978	8,600	254,200	–	–	–	–	–
		237,000[c]					
1979	8,600	254,200	–	–	–	–	–
		189,000[b]					
1980	11,800	206,100	200	1,300	3,420[c]	1,370[c]	–
					5,600[d]		
1981	11,700	204,900	400	2,900	–	–	–
		187,000[b]					
1982	13,300	239,200	400	3,500	2,970[c]	1,600[c]	–
					3,200[d]		
1983	15,500	278,200	400	4,000	1,560[d]	2,130[c]	–
1984	19,900	257,200	400	4,000	3,110	2,490	116[b]
1985	17,800	254,500	400	4,000	3,013	2,420	82[b]
		236,000[b]					
1986	17,600	243,600	1,200	5,100	6,770[c]	5,000[c]	–
1987	17,500	224,400	1,200	5,100	7,480[c]	5,670[c]	–
1988	17,100	212,200	1,200	5,100	2,710[c]	4,110[c]	–
1989	16,600	200,400	1,300	5,100	3,100	2,200	100
			5,400[e]	5,500[e]			
1990	15,786[f]	232,600	1,200	5,100	2,712	1,813	97
			6,600[e]	5,600[e]			
1991	15,422[f]	196,200	1,400	5,100	2,660	1,739	97
			9,700[e]	6,100[e]			
1992	14,147[f]	182,000[b,c]	–	–	2,118[b]	1,456[b]	91[b]
1993	12,528[f]	136,900	1,300	5,100	1,960	1,049	89
		145,000[f]					
1994	10,206[f]	97,700	900	1,300	1,619	933	82
1995	8,445[f]	129,400	1,000	1,000	1,366	726	56

(continued)

Table 2.12 (continued)

Year	Dust	SO_2	CO	NO_x	Ni	Cu	Co
1996	7,729[f] 9,800	110,500	2,300	1,000	1,309	699	41
1997	8,092[f]	140,200	1,500	700	1,348	761	37
1998	7,246[f] 8,500	88,600	1,400	700	1,304	873	35
1999	6,016[f] 7,200	46,100	2,000	800	1,128	856	32
2000	9,900	45,800	4,000	1,500	1,216	873	34
2001	9,100	43,900	3,600	1,300	1,200	827	44[b]
2002	7,700	43,900	3,800	1,200	818[f] 910	696	–
2003	7,200	42,100	3,800	800	734[f]	699	10
2004	6,500	37,900	2,900	800	687	580	12
2005	6,500	41,100	2,400	700	501[f]	608	12

Non-referenced values were extracted from Emissions of Pollutants in Russia (1966–2006).
Other data sources:
[a] Alexeyev (1993).
[b] Barcan (2002b).
[c] Mokrotovarova (2003).
[d] V. Nikonov (personal communication, 1998).
[e] Kryuchkov (1993b).
[f] Miroevskij et al. (2001), the data refer to the smelter only.
[f] Severonikel smelter (statistical forms TP-2).

impact resulted in slight soil acidification and severe contamination by metals. The reported peak concentrations in soils were 4,622 mg/kg of copper, 9,288 mg/kg of nickel, and 210 mg/kg of zinc (Barcan & Kovnatsky 1998; V. Barcan, personal communication, 2006).

By the time of the first survey (1966), the contaminated area covered approximately 6,000 km (Kozlov & Barcan 2000). In 1983, sulphur deposition exceeded the regional background over 60,000 km^2, forming a continuous polluted zone centred at Monchegorsk and extending over Kovdor, Olenegorsk, Kirovsk and Kandalaksha (Kryuchkov & Makarova 1989); however, there still was a gap between this area and the contaminated area around Nikel and Zapolyarnyy. These polluted areas merged by the late 1980s–early 1990s, and a potentially critical deposition of sulphur was exceeded over an area of 150,000 km^2, 32,000 km^2 of which was in Finland and 19,000 km^2 in Norway (Tuovinen et al. 1993). However, according to official reports, a doubling of pollutant deposition (relative to the regional background) during the period 1986–1991 was recorded only for 800 km^2 (Prokacheva et al. 1992).

Habitat Transformation due to Human Activity

Visible signs of forest damage around Monchegorsk appeared immediately after the beginning of smelting. In the early 1950s, clear changes in forest vegetation were detected within 2–3 km from the smelter (Kozlov & Barcan 2000). Industrial barrens (please see color plates 34–39 in Appendix II) appeared in the early 1960s, and by the early 1990s, they were estimated to cover 200–250 km^2, surrounded by 400–500 km^2 of dead forests (please see color plates 32 and 33 in Appendix II) (Kryuchkov 1993a, c; Tikkanen & Niemelä 1995; Rigina & Kozlov 2000; Kozlov & Zvereva 2007a).

Brief History of Environmental Research

The effects of emissions of the Monchegorsk smelter on terrestrial ecosystems have been systematically studied since 1971, and the impact zone of this polluter is explored most thoroughly on a global scale. Some 30 research teams have been working in the area affected by the Severonikel smelter since 1970s; the results of the research are reported in over 1,000 publications, including approximately 20 monographs. For the history of environmental research and references for the most important studies of Russian scientists, consult Kozlov et al. (1993) and Kozlov and Barcan (2000); the results of the Finnish project were summarised by Tikkanen and Niemelä (1995). A somewhat outdated list of relevant publications is available at www.ngu.no/Kola/bibliodb.html. In spite of the high number of studies, there remain a number of knowledge gaps (identified by Rigina & Kozlov 2000). The extensive overview of recent findings is given by the AMAP (2006) assessment.

Perception of the Environmental Situation

Although severe damage to forests around Monchegorsk has been clearly visible for decades, neither the Soviet nor the Russian governments invested money in searching for solutions to the ecological problems of the Kola Peninsula. Even publication of the alarming letter ‘Smoke over the reserve’ by O. I. Semenov-Tian-Schanskij and A. B. Bragin in the central communist newspaper ‘Pravda’ in 1979 had no effect (Kozlov & Barcan 2000). Later, the distribution of ‘negative’ ecological information was prohibited until 1989, when the appearance of publications warning of the threat to nature led to mass actions by local residents calling for an end to the poisoning of the environment. However, since 1990 the smelter has been privately owned, leaving no hope for governmental funding of nature protection measures. Furthermore, on 12 May 1990, the director of the Severonikel smelter declared in the local newspaper that reducing production is the only realistic way to reduce emissions, but that this would lead to substantial cutting the workforce. Thus, in a town inhabited mainly by smelter workers, every family would be affected (Kryuchkov 1993c).

There is no doubt that the inhabitants of Monchegorsk were and continue to be chronically exposed to exceptionally high levels of pollutants. The concentrations of nickel and copper in local vegetables, berries and mushrooms greatly exceed the maximum tolerable limits, and the extensive health problems reported for the residents of these cities are obviously related to the emissions of non-ferrous metallurgy. However, local residents, although regularly informed through the press and other mass media of the possible adverse effects of contaminated air and food, continue to collect berries and mushrooms near the smelter and to grow potatoes and vegetables within severely contaminated areas (Kozlov & Barcan 2000). The situation started to change in the late 1990s, with a decrease in smelter emissions and implementation of a municipal re-greening program widely advertised by mass media (Petrov 2004; Timofeeva 2005). The environmental situation at Monchegorsk was recently debated on one of the local web forums (www.hibiny.ru).

2.2.2.10 Nadvoitsy, Russia: Aluminium Smelter (Color Plates 40–42 in Appendix II)

Location and Environment

Nadvoitsy is a small (population 10,600; data from 2006) urban-type settlement in the Segezhsky district of the Republic of Karelia. It is located on the shore of Vygozero Lake, 240 km north of Petrozavodsk (Fig. 2.11). Forests around Nadvoitsy (please see color plate 40 in Appendix II) were originally dominated by Scots pine, with a mixture of Norway spruce and frequent occurrences of *Sphagnum* and aapa mires.

Pre-industrial History

The oldest settlements in the area surrounding Nadvoitsy date to the Stone Age. Prior to building of the railway between St. Petersburg and Murmansk, the area was only sparsely populated. The railway station at Nadvoitsy was established in 1915. Neither agriculture nor forestry had affected the surrounding forest prior to the 1930s, when a pulp and paper factory was built in the nearby town of Segezha.

Industrial History

The aluminium smelter, located on the southern outskirts of Nadvoitsy, was commissioned in 1954. Its capacities were expanded in 1961, allowing production of 60,000 t of aluminium (in pigs, silumin, powder, and alloys) annually. Annual production of aluminium increased to 68,000 t in the late 1990s (US Geological Survey 1999). The new electrolysis production line, using technology developed by Kaiser (USA), was launched in 1999, leading to both an increase of aluminium production (80,000 t in 2006) and a decrease in emissions. Building of new emission control systems (dry gas-washing) started in 2006. Following implementation of the new technologies, the number of employees decreased from 3,000 in the early 1990s to 2,000 in 2001 (Boltramovich et al. 2003) and 1,458 in 2006 (www.sual.ru). The town's economy is fully dependent on the smelter.

Emissions Data

Since there are no other industries in the town, the aluminium smelter is responsible for a vast majority of the total emissions of sulphur dioxide and nitrogen oxides at Nadvoitsy, and for the entire emission of fluorine (Table 2.13).

Pollution Loads and the Extent of the Contaminated Territory

Ambient concentrations of pollutants in Nadvoitsy have been monitored since 1978; the peak reported values were 0.30 mg/m^3 of SO_2 in 1981, and 0.27 mg/m^3 of HF in 1982 (Emissions of pollutants in Russia 1966–2006). In 1990, ambient air monitored 1,200 m north–northwest of the smelter contained on average 0.037 mg/m^3 of SO_2, 0.026 mg/m^3 of NO_x and 0.0084 mg/m^3 of HF, with peak values of 0.15, 0.08 and 0.027 mg/m^3, respectively (Ministry of the Environment of Finland 1991b). On the other hand, it was reported (Kozlovich 2006) that ambient fluorine

Table 2.13 Aerial emissions (t) from industrial enterprises at Nadvoitsy, Russia

Year	Dust	SO_2	CO	NO_x	F-containing dust	HF
1978	1,700	12,900	7,200	200	–	360
1979	1,700	12,900	7,200	200	–	360
1980	6,200	–	7,200	200	–	400
1981	4,700	1,500	16,200	200	–	400
1984	5,000	1,500	7,500	100	–	410
1985	4,600	1,500	7,500	100	3,330	400
1986	4,700	1,400	7,500	100	3,330	400
1987	6,100	2,300	5,200	100	4,704	375
1988	5,900	2,300	5,100	100	4,700	373
1989	6,000	2,200	3,700	100	4,487	437
1990	5,700 3,450[a]	2,200	3,500	100	690[a]	410[a]
1991	4,300	1,800	3,300	100	–	–
1993	3,900	1,900	3,300	100	445	216
1994	4,100	1,600	4,000	100	–	240
1995	4,100	1,400	3,700	50	–	–
1996	4,100	1,200	3,600	40	–	–
1997	4,000	1,000	3,000	40	–	246
1998	3,400	1,200	3,000	50	–	–
1999	3,500	1,300	3,000	40	–	283
2000	4,300	1,400	3,200	40	–	363
2001	4,300	1,200	3,500	100	–	–
2002	3,400	1,200	2,700	40	–	288
2003	3,000	1,200	2,700	70	–	318
2004	4,200	1,000	2,600	60	–	497
2005	3,000	1,200	2,400	70	–	313

Non-referenced values were extracted from Emissions of Pollutants in Russia (1966–2006).
Other data sources:
[a] Ministry of the Environment of Finland (1991b).

in Nadvoitsy during 2 days of measurements in 2005 was 0.021 and 0.230 mg/m^3 (i.e., 4 and 46 times higher than the sanitary limit of 0.005 mg/m^3).

A doubled level of pollutant deposition (relative to the regional background) during the period 1986–1991 was recorded for 40 km^2 around Nadvoitsy (Prokacheva et al. 1992). At the same time, the footprint of the plant had not been detected in the course of mapping of the entire territory of Karelia for sulphur and metal concentrations in green mosses and forest litter (Fedorets et al. 1998).

Habitat Transformation due to Human Activity

Although we have not observed any dead stands near the smelter in 2004–2007, alarming newspaper reports claimed that ‘emissions have turned a 100-m belt of the surrounding taiga into a lifeless zone of dead trees’ (Baiduzhy 1994). Slight signs of forest deterioration (please see color plate 41 in Appendix II) are visible only within 1–2 km from the smelter, but local heating systems and recreation obviously share responsibility for the lower vitality of forests around Nadvoitsy.

Brief History of Environmental Research

We failed to locate any scientific publication analysing the impact of the aluminium smelter on terrestrial ecosystems. The data from environmental and health surveys conducted by scientists from the Petrozavodsk State University in the early 2000s have not been published and will remain unpublished according to the agreement with the Nadvoitsy aluminium plant that financed the research (T. Karaperyan, personal communication, 2008). On the basis of this study, the smelter administration reported an absence of ecological problems (Lukin & Gavrilova 2004), but it did not disclose the actual results of the research.

Perception of the Environmental Situation

Since the late 1980s–early 1990s, the Nadvoitsy aluminium plant has become the centre of the Greens’ attention. An inspection (results of which we were unable to trace) produced a shocking report about an extreme excess of fluorine in the drinking water. A furor erupted, with a number of alarming papers published in newspapers and on the web (Baiduzhy 1994; Efron 1994; Kozlovich 2004). These papers claimed that there was a high degree of occupational illness, as well as outstanding development of fluorosis among the younger generation of Nadvoitsy (Efron 1994). However, according to another newspaper’s report (Zlobin 2002), the significant worsening of the ecological situation around the works, which took place in the 1970s, is at present fully overcome. In 2001, emissions of substances detrimental to human health were reported to be within allowable limits. Thus, the ‘ecological catastrophe’ neither exists, nor is it anticipated (Zlobin 2002). However, it seems that these results have not convinced environmental activists (Kozlovich 2006), and the situation in Nadvoitsy was recently publicised in Northern Europe (Lorentzen 2005).

2.2.2.11 Nikel, Russia: Nickel-Copper Smelter, and Zapolyarnyy, Russia: Ore-Roasting Plant (Color Plates 43–47 in Appendix II)

Location and Environment

Nikel (the Finnish name is Kolosjoki), the administrative centre of the Pechengsky district, is an urban-type settlement (population 15,900; data from 2005) in the Murmansk Region. It is located on the shores of Kuetsjärvi (Kuets Lake) 195 km northwest of Murmansk and 7 km from the Norwegian border. Zapolyarnyy is a small (population 18,200; data from 2007) town located 25 km east of Nikel, halfway from Nikel to Pechenga (Fig. 2.12).

Both Nikel and Zapolyarnyy are situated in the north boreal and low-alpine vegetation regions close to the Arctic tree line. Pre-industrial vegetation of the landscape surrounding the towns, with hills of up to 600 m above sea level, was patchy, with sparse mixed forests of Scots pine and mountain birch to the south of Nikel (please see color plate 45 in Appendix II), and birch woodlands and tundras (please see color plate 44 in Appendix II) to the northeast.

Pre-industrial History

The ancestors of the indigenous population of Lapland, Saami, appeared in the Pechenga area in approximately 6000 BC. From the beginning of the sixteenth century, Russians (Pomors) built their temporary settlements here for fishing and trade. The Pechenga area (the Finnish name is Petsamo) was part of Russia between 1533 and 1920 and then became part of Finland. Discovery of the nickel ore deposits in the Pechenga Mountains (Petsamo-tunturi) in 1934 made this region very important in a strategic sense because nickel was in demand by military industry. The settlement of Kolosjoki was built 40 km southwest of the Pechenga Monastery, on approximately the same site where Pazrestkij Pogost (the Finnish name is Vanhatalvikylä) existed from the sixteenth century. The area became, again, a part of Russia (the Soviet Union at that time) in 1944.

Industrial History

In 1934, the Canadian company INCO obtained concessions for the entire ore-bearing area of 135 km^2. Preparatory works started in 1935, and mining was launched in 1940. In 1941, the area was occupied by Germany, and smelting (at the factory built by INCO of Canada) began in 1942. The smelter was very modern; it had the biggest convertors and the tallest (165 m) smokestack in Europe at that time. The mine and the smelter worked at full capacity until 1944, producing in total 16,000 t of nickel, 90% of which was exported to Germany. In 1944, there were 1,570 workers, including 360 war prisoners. The smelter was partially destroyed by retreating German troops in 1944, but it was reconstructed soon after (thanks to documentation bought by the Soviet government from the former Finnish owners for USD 20 million) and recommenced operations in 1946. The settlement of Zapolyarnyy was established in 1955 in association with the mining and processing of copper-nickel ores; it was granted town status in 1963.

Now Pechenganikel is a subsidiary of Norilsk Nikel, with four open pits, an enrichment plant, a roasting shop, and smelting and sulphuric acid production shops; it employs 10,000 workers. Its principal products are matte (processed on a tolling basis at the Severonikel smelter in Monchegorsk) and sulphuric acid. However, since smelting facilities at Nikel require extensive reparation, it is likely that the smelter will soon be (partially) closed, with simultaneous extension of the smelting facilities at Monchegorsk (BarentsObserver 2007).

Emissions Data

The smelter in Nikel contributed 98.0–99.9%, and the ore roasting factory in Zapolyarnyy contributed 90.6–99.7%, of aerial emissions reported for these towns during the period 1989–1999 (Tables 2.14, 2.15; Emissions of pollutants in Russia 1966–2006).

Pollution Loads and the Extent of the Contaminated Territory

Ambient concentrations of pollutants in both Nikel and Zapolyarnyy have monitored since 1967. The peak reported values for Nikel were 5.00 mg/m^3 of dust in 1978, 7.14 mg/m^3 of SO_2 in 1971, and 1.18 mg/m^3 of NO_x in 1978. The peak reported values for Zapolyarnyy were 3.25 mg/m^3 of SO_2 in 1979, and 1.87 mg/m^3 of NO_x in 1967 (Emissions of pollutants in Russia 1966–2006).

In spite of a substantial emissions decline (Table 2.14), high levels of ambient sulphur dioxide still occur at Nikel; for example, concentrations of 2.6 mg/m^3 (exceeding the sanitary limit of 0.05 mg/m^3 by a factor of 52) were officially reported on 4 and 15 July 2007 (www.kolgimet.ru). Importantly, the levels of ambient sulphur dioxide measured by an international research project from 1992 to 2005 were around three times higher than those officially reported by the Murmansk Hydrometeorological service, and they are considered unacceptably high (Stebel et al. 2007).

The long-term emissions impact resulted in slight soil acidification and severe contamination by metals. The peak reported metal concentrations in soils were 3,489 and 1,020 mg/kg of copper, and 2,990 and 2,230 mg/kg of nickel (for Nikel and Zapolyarnyy, respectively) (Niskavaara et al. 1996; Reimann et al. 1998; Kozlov & Zvereva 2007a). During the period 1987–1989, annual depositions of sulphur and nitrogen in Nikel were 3,300 and 200 kg/km^2, respectively (Vasilenko et al. 1991).

Table 2.14 Aerial emissions (t) from industrial enterprises at Nikel, Russia

Year	Dust	SO_2	CO	NO_x	Ni	Cu	Co
1943	–	55,000[a]	–	–	–	–	–
1971	–	131,800	–	–	–	–	–
1972	7,300	255,500	–	–	–	–	–
1973	7,300	255,500	–	14,600	–	–	–
1974	7,300	335,800	–	14,600	–	–	–
1975	7,300	335,800	–	14,600	–	–	–
1978	5,200	339,000	–	14,600	–	–	–
1979	5,200	339,000	–	14,600	–	–	–
1980	5,000	328,200	100	200	–	–	–
1981	4,800	290,100	100	–	–	–	–
1982	4,600	292,800	100	200	–	–	–
1983	4,700	293,200	200	400	240	170	10
1984	4,700	290,500	100	–	220	140	10
1985	4,400	274,900	200	100	210	130	10
1986	4,300	261,100	200	100	220	150	10
1987	4,000	257,900	200	100	190	130	6
1988	4,100	211,400	200	100	160	140	20
1989	3,900	199,600	200	200	170	110	10
			800[b]				
1990	3,900	190,100	200	200	136	92	5
			4,200[b]	600[b]			
1991	3,900	189,800	200	200	131	88	5
			3,800[b]	600[b]			
1993	3,500	160,600	300	200	130	87	5
1994	3,700	129,200	300	200	136	82	5
1995	3,900	175,400	340	160	137	85	5
1996	3,300	183,700	300	100	136	92	5
1997	3,700	183,500	300	100	155	96	5
1998	2,400	125,500	200	100	143	93	5
1999	2,500	90,100	700	200	155	100	5
2000	2,600	85,600	500	100	171	108	6
2001	2,600	85,600	500	100	171	108	–
2002	2,800	62,300	200	200	150	83	–
2003	2,400	60,600	100	200	149	83	5
2004	2,300	56,400	100	200	154	86	5
2005	2,200	55,500	70	10	157	88	5

Non-referenced values were extracted from Emissions of Pollutants in Russia (1966–2006).
Other data sources:
[a] Honkasalo (1989).
[b] Kryuchkov (1993a).

Satellite data showed that the total area affected by air pollution around Nikel increased from 400 km² in 1973 to more than 3,900 km² in 1988, and the area remained this size during the early 1990s (Høgda et al. 1995; Tømmervik et al. 1995). According to another estimate, between 1986 and 1991 a doubling of pollutant deposition (relative to the regional background) was recorded for 1,200 km² (within the Russian Federation only) around Nikel, Zapolyarnyy and Pechenga (Prokacheva et al. 1992).

Table 2.15 Aerial emissions (t) from industrial enterprises at Zapolyarnyy, Russia

Year	Dust	SO_2	CO	NO_x	Ni	Cu	Co
1971	9,900	52,900	–	–	–	–	–
1972	9,900	58,000	–	–	–	–	–
1973	10,950	60,200	–	3,700	–	–	–
1974	10,950	63,900	–	3,700	–	–	–
1975	10,950	63,900	–	3,700	–	–	–
1978	5,300	56,700	–	–	–	–	–
1979	5,300	60,000	–	8,600	–	–	–
1980	5,500	70,600	300	300	–	–	–
1981	6,300	71,300	300	–	–	–	–
1982	5,400	65,100	300	200	–	–	–
1983	5,500	75,500	300	300	190	90	–
1984	5,200	74,900	300	200	190	90	8
1985	4,600	79,300	300	200	170	90	10
1986	4,100	81,500	200	200	160		
1987	4,100	79,700	200	200	200	100	5
1988	4,100	78,600	300	200	200	100	5
1989	4,100	77,800	400	300	130	90	5
	4,500[a]		3,400[a]	1,200[a]			
1990	4,100	63,700	400	300	165	88	6
	4,500[a]		5,200[a]	1,500[a]			
1991	4,100	67,600	400	300	148	–	–
	4,500[a]		4,700[a]	1,400[a]			
1993	3,900	66,600	500	300	152	74	5
1994	6,400	69,200	500	300	161	81	5
1995	6,500	70,200	400	300	161	93	6
1996	5,900	52,500	400	200	162	85	5
1997	6,100	69,900	400	300	166	87	6
1998	5,800	65,200	400	200	180	95	6
1999	5,600	62,500	1,000	200	175	93	6
2000	5,500	65,600	900	200	183	98	6
2001	5,500	65,600	900	300	183	98	–
2002	5,500	61,600	70	300	183	86	–
2003	4,600	63,700	60	300	180	84	–
2004	4,300	56,000	100	300	175	82	–
2005	3,900	51,400	200	300	171	84	–

Non-referenced values were extracted from Emissions of Pollutants in Russia (1966–2006).
Other data sources:
[a] Kryuchkov (1993b).

Habitat Transformation due to Human Activity

Since the original vegetation was patchy, with a predominance of birch woodlands, the development of industrial barrens did not modify the landscape as much as in forested regions, such as Monchegorsk or Sudbury. The appearance of barrens is dated to the early 1960s for Nikel and the late 1960s for Zapolyarnyy. The overall extent of barren and semi-barren landscapes (please see color plates 45–47 in Appendix II) around these two towns with overlapping impact zones, was 340 km^2 in 1973 and 687 km^2 in 1999 (Tømmervik et al. 2003; Kozlov & Zvereva 2007a).

Brief History of Environmental Research

The effects of aerial emissions arising from Nikel and Zapolyarnyy on terrestrial biota were not properly documented until the late 1980s, in particular due to restricted access to this territory. However, the situation changed in the early 1990s, especially due to international concern about transboundary pollution effects. The studies mostly reported the effects on vegetation, including mosses, lichens, and vascular plants (Aamlid 1992; Tømmervik et al. 1998, 2003; Aamlid et al. 2000; Aamlid & Skogheim 2001; Chernenkova 2002; Bjerke et al. 2006). An extensive overview of recent studies is given by the AMAP (2006), with the most recent data summarised by Stebel et al. (2007).

Perception of the Environmental Situation

The industrial complex of Nikel and Zapolyarnyy poses its main threat to aquatic and terrestrial environments in the joint Norwegian, Finnish and Russian border area. The awareness of this situation exists both nationally and internationally (Stebel et al. 2007), although the Finnish people have not been concerned as much recently about the emissions from Nikel as they were in the 1980s–1990s. In 2007, pollution at Nikel became the focal point of several alarming publications (Popova 2007), and a criminal investigation was conducted in association with the excess of sulphur dioxide above sanitary limits and subsequent forest damage (nn.gazetazp.ru). The situation was widely debated, especially in Norway, and the Norwegian authorities even recommended evacuating the city (www.Euroarctic.com). People on the Norwegian side were indeed worried by this situation, but there was no panic (H. Tømmervik, personal communication, 2008).

2.2.2.12 Norilsk, Russia: Nickel-Copper Smelters (Color Plates 48–50 in Appendix II)

Location and Environment

Norilsk (population 209,300; data from 2007) is a heavily industrialised, major city in the Krasnoyarsk Region, located on the Taimyr Peninsula nearly 2,000 km to the north of Krasnoyarsk, and 300 km north of the Arctic Circle (Fig. 2.13). The city is situated on one of the largest nickel deposits on Earth, at the foot of the 1,700 m high Putoran Mountains. It is the northernmost city with a population over 100,000 on the planet, and one of two large cities in the continuous permafrost zone (the second one is Yakutsk, Russia).

Norilsk is situated approximately at the border between deciduous shrub tundra and sparse, 200–300 years old sub-tundra forests (please see color plate 48 in Appendix II). A detailed description of plant communities around Norilsk in 1962–1963 (Moskalenko 1965) to a large extent reflects the pre-industrial situation.

At about that time, the forests formed by Siberian larch or Gmelinii larch (*Larix gmelinii*) with white birch and Siberian spruce, covered 43% of the region (Kovalev & Filipchuk 1990).

Pre-industrial History

Archaeological evidence suggests that the copper ore deposits were first discovered and used in small amounts during the Bronze Age (Kunilov 1994; cited after Blais et al. 1999). For centuries, this area was only sparsely populated by natives who lived from hunting, fishing, and reindeer herding. The first known mining and smelting operations, resulting in production of 3 t of copper, are dated 1868. However, systematic exploration began only in the 1920s, and the first building in this unpopulated area was erected in 1921. The settlement of Norilsk was founded by the end of the 1920s; however, the official date is traditionally set to 1935, when Norilsk was expanded as a settlement for the mining-metallurgic complex. Town status was granted in 1953.

Industrial History

Initial exploration drilling began in the Norilsk area in 1923. The government of the USSR created in 1935 the Norilsk Combine, which used forced labour until the mid-1950s. The first mine to remove sulphide ores was operational in 1938, and the first copper-nickel matte was produced in 1939. The second line (the recent nickel smelter) was launched in 1942 using equipment evacuated from Monchegorsk; the copper smelter and the coke production plant began operations between 1947 and 1949. The third smelter, Nadezhda, was launched in 1979; it produces copper, fainstein, selenium, tellur, and concentrates of precious metals including platinum, palladium, Ro, Ru, Ir, Os, silver and gold. This smelter also has sulphur-processing facilities. By the late 1990s, these three smelters produced approximately 50% of Russia's nickel, 40% of its copper, 70% of its cobalt and 90% of its platinum group metals. A joint-stock company, Norilsk Nikel (created in 1993), now employs 56,000 inhabitants of Norilsk.

Emissions Data

Non-ferrous smelting is responsible for nearly 100% of emissions of sulphur dioxide, 77.5% of dust, and 67.6% of emissions of carbon oxide and nitrogen oxides at Norilsk (Savchenko 1998). The peak annual emissions of sulphur dioxide exceed 2.5 million tons (Table 2.16), contributing nearly 4% of global emissions (estimate after Lefohn et al. 1999).

Concentrations of nickel and copper in dust (according to Menshchikov & Ivshin 2006) suggest that metal emissions during the period 1990–1997 were much

Table 2.16 Aerial emissions (t) from industrial enterprises at Norilsk, Russia

Year	Dust	SO_2	CO	NO_x	Ni	Cu
1965	–	400,000[a]	–	–	–	–
1970	93,100	1,803,100	–	–	–	–
		750,000[a]				
1971	93,100	1,825,000	–	–	–	–
1972	143,100	1,825,000	–	–	–	–
1973	142,350	1,825,000	–	–	–	–
1974	142,350	1,825,000	–	–	–	–
1975	142,350	1,825,000	–	–	–	–
		1,225,000[a]				
1976	–	1,380,000[b]	–	–	–	–
1978	44,000	1,580,600	–	1,000	–	–
		1,490,000[b]				
1979	44,000	1,749,000	23,100	15,000	–	–
	59,750[c]	1,540,000[b]				
1980	41,000	1,622,700	27,800	31,800	–	–
	69,850[c]	1,742,000[b]				
1981	41,000	1,994,900[d]	29,400	29,400	–	–
	66,650[c]	1,880,000[b]				
1982	65,100	2,190,000	44,000	29,400	–	–
	62,900[c]	2,402,000[d]				
1983	73,300	2,520,300	58,800	29,000	–	–
	64,000[c]					
1984	52,600	2,195,000[b]	31,200	29,100	–	–
	71,450[c]	2,447,200				
		2,647,700[d]				
1985	47,400	1,890,000[b]	20,400	28,000	–	–
	59,750[c]	2,418,900[e]		29,600[e]		
		2,724,300[d]				
1986	35,400	1,850,000[b]	20,400	18,700	–	–
	54,950[c]	2,327,300		20,500[e]		
1987	33,800	1,760,000[b]	18,800	19,200	–	–
	42,150[c]	2,325,200[e]		20,800[e]		
1988	32,800	1,740,000[b]	18,600	16,900	–	–
	40,000[c]	2,244,300		18,600[e]		
		2,350,000[a]				
1989	30,900	1,710,000[b]	12,900	18,400	–	–
		2,207,500				
		2,300,000[a]				
1990	31,700	1,690,000[b]	15,000	20,200	–	–
		2,201,700				
1991	31,700	1,568,000[b]	7,790[a]	17,990[a]	1,300	3,021
		2,201,700	15,000	20,200		
		2,397,000[a]				
1992	29,710[a]	2,118,000[a]	10,040[a]	19,280[a]	–	–
1993	27,200	1,862,800	9,900	17,300	1,089	2,469
1994	26,600	1,860,300	10,400	14,700	1,284	2,382
1995	27,500	1,961,300	8,900	16,000	1,449	2,415
1996	24,100	2,014,400	37,400	12,200	1,198	2,151
1997	26,000	2,104,800	16,700	11,300	1,432	1,958
1998	20,100	2,064,900	15,400	11,600	916	1,750

(continued)

Table 2.16 (continued)

Year	Dust	SO_2	CO	NO_x	Ni	Cu
1999	20,300	2,104,000	12,400	10,700	3,000[f]	8,250[f]
					793	1,752
2000	16,800	2,078,800	13,200	10,500	596	1,069
2001	15,000	2,050,100	11,500	10,900	595	1,069
2002	14,200	1,965,000	12,400	9,300	629	–
2003	13,900	1,846,600	14,500	8,300	558	562
2004	–	2,011,200	–	8,200	556	661
2005	12,400	1,955,300	10,200	9,000	539	626

Non-referenced values extracted from Emissions of Pollutants in Russia (1966–2006).
Other data sources:
[a] Savchenko (1998).
[b] Kharuk (2000).
[c] Kharuk et al. (1996).
[d] Kovalev and Filipchuk (1990).
[e] Bezuglaya et al. (1991).
[f] Koutsenogii et al. (2002).

higher than officially reported (Table 2.16), comprising 3,900 t of copper, 3,100 t of nickel, and 84 t of cobalt annually. Other data sources reported annual emissions of 1,800 t of copper, 4,000 t of nickel, and 65 t of vanadium in the early 1990s (Nilsson et al. 1998; cited after Kharuk 2000) and of 3,000 t of copper and 8,250 t of nickel in 1999 (Koutsenogii et al. 2002). Ore chemistry and annual production data suggest that in 1994 smelters at Norilsk also emitted 150 t of lead, 29 t of zink, and less that 1 t of arsenic and antimony (Boyd et al. 2009). It was even claimed that 'heavy metal pollution in the area is so severe that the soil itself has platinum and palladium content which is feasible to mine' (Kramer 2007). All this information casts doubt on the reliability of official emissions data.

The strategic goal announced by Norilsk Nikel in 2005 is a fivefold decrease of sulphur dioxide emissions (i.e., to 426,000 t or less) by 2015 (Ershov et al. 2005). By 2010, Norilsk Nikel plans to implement large investment projects aimed at reconstruction of production facilities to reduce the environmental impact. Actions toward the gradual decrease of emissions resulted in 2006 in a decline of SO_2 emissions by 0.84%, and of dust emissions by 12.9%, relative to 2005 (Norilsk Nikel 2007).

Pollution Loads and the Extent of the Contaminated Territory

Ambient concentrations of pollutants in Norilsk have been monitored since 1968; the peak reported values were 8.50 mg/m^3 of dust in 1978, 68.4 mg/m^3 (sic!) of SO_2 in 1981, and 0.43 mg/m^3 of NO_x in 1978. Even in 1990, the average annual concentration of SO_2 exceeded the sanitary limit (0.05 mg/m^3) by a factor of 2–3, with a peak value of 19 mg/m^3 (Bezuglaya 1991).

In 1987–1989, annual depositions of sulphur and nitrogen in Norilsk were 12,200 and 1,200 kg/km^2, respectively (Vasilenko et al. 1991). The concentration of copper in the upper soil horizon 600 m from the copper smelter was 20,600 mg/kg (Gorshkov 1997), and soils within approximately 1,350 and 1,000 km^2 contained copper and nickel, respectively, in concentrations exceeding the regional background by a factor of 10 or more (Igamberdiev et al. 1994). Dust deposition exceeded the background values by a factor of 100 or more for 70 km^2, with peak values (1,000–1,100 t/km^2) 750 times higher than the regional background (Chekovich et al. 1993).

In spite of extreme emissions of sulphur dioxide, soil, snow and water of local lakes were slightly alkaline due to high concentrations of base cations (Blais et al. 1999; Menshchikov & Ivshin 2006). Still, the lowest pH values of soil in the impact zone were 4.4, compared with 5.3–7.0 in unpolluted areas (Kharuk 2000).

Norilsk is the only city whose individual footprint is clearly visible on a map showing the annual deposition of sulphur for the entire territory of the former USSR (Vasilenko et al. 1991). According to this map, the deposition exceeded the regional background (less than 250 kg/km^2) over 246,000 km^2. According to another estimate, the overall extent of the contaminated zone over a 'relatively clean' background in 1989 was approximately 34,200 km^2 (including both land and lakes); the strongly contaminated zone covered 2,300 km^2 (Klein & Vlasova 1992). At the same time, another report indicated a doubling of pollutant deposition (relative to the regional background) during the period 1986–1991 for 7,000 km^2 (Prokacheva et al. 1992).

Although the external border of the metal-contaminated area to the north of the smelter extended less than 100 km (Allen-Gil et al. 2002), aerosols emitted by Norilsk smelters were reported to reach both Severnaya Zemlya and Franz Josef Land, thus substantially contributing to regional contamination of the Arctic (Shevchenko et al. 2003).

Habitat Transformation due to Human Activity

We date the development of the industrial barrens around Norilsk to the mid-1950s. Different data sources suggest that the extent of barren and semi-barren sites around Norilsk in 1990s was around 4,000 km^2 (Kozlov & Zvereva 2007a). The initial deforestation, leading to the rapid development of industrial barrens, was created here for a very specific reason; since prisoners were used extensively for construction of the Norilsk plant, a buffer of 3–4 km was cut around each of the prison camps (Kharuk 2000).

The first report of forest decline near Norilsk is dated 1968; by this time, 50 km^2 of forest was dead (Kharuk et al. 1995). The extent of forest damage increased from 3,384 km^2 in 1976 (including 446 km^2 of dead forests) to 5,452 km^2 in 1986 (Kovalev & Filipchuk 1990). Other data sources suggest that the effects of emissions on vegetation in the late 1980s–early 1990s were detectable over 35,500 km^2 (Menshchikov 1992), or even 70,000 km^2 (Chekovich et al. 1993). The external border of declining forests (please see color plate 49 in Appendix II) in 1987 was located 60 km to the east and 120 km to the southeast. Visual signs of larch damage, such as needle discoloration, were detected up to 200 km from the polluter (Kovalev & Filipchuk 1990; Kharuk et al. 1995). In 2002, we observed necroses on white birch leaves at our most distant plot, located 96 km east of Norilsk. Still, some 'optimistic' publications report that '60–70 km from Norilsk [one can see] virgin sub-tundra forests in their original beauty' (Grachev 2004, p. 102).

Damage to terricolous lichens was detected at distances of 200–250 km (Kharuk 2000), or even 300 km from the smelters (Otnyukova 1997). The lichen desert area in 1989 was estimated to cover 3,000 km^2, and lichens over 6,000 km^2 exhibited retarded growth and visual signs of damage (Klein & Vlasova 1992).

Brief History of Environmental Research

Although scientific exploration of the pollution impact on terrestrial ecosystems around Norilsk started no later than the 1970s, almost no information was published before the early 1990s. The majority of publications about the Norilsk environment are too general and only rarely provide solid conclusions supported by both a description of methodology and statistical analysis. The book by Menshchikov and Ivshin (2006) is especially disappointing due to incomplete presentation of unbalanced data sets (or presentation of relative values only), a messy structure (i.e., distance of some study plots from the polluter remains unknown; data on plant growth and contamination originate from different subsets of study plots), and an absence of straightforward conclusions.

The reported biotic effects of pollution are limited to soil microbiota (Raguotis 1989; Kirtsideli et al. 1995), vitality of conifers (measured using an arbitrary index), decline in the radial increment of larch and spruce (albeit without statistically sound comparison between polluted and unpolluted sites; Simachev et al. 1992; Demyanov et al. 1996; Schweingruber & Voronin 1996; Menshchikov & Ivshin 2006), decline in forest biomass (Polyakov et al. 2005), changes in vegetation structure (Varaksin & Kuznetsova 2008), and remote sensing data outlining the extent of the pollution damage (Kharuk et al. 1995, 1996, Tutubalina & Rees 2001; Zubareva et al. 2003). For an overview of the environmental situation around Norilsk, consult Kharuk (2000). The acidity status of soils is discussed in the AMAP (2006) report.

Perception of the Environmental Situation

The Norilsk phenomenon can be seen as the largest ecological catastrophe on a global scale (Kharuk et al. 1996). The situation in Norilsk has long been attracting public attention on both national and international scales, and many alarming reports have been published in past years. The broad awareness of this particular case is emphasised by description of the pollution problem at Norilsk in Wikipedia (en.wikipedia.org). The Blacksmith Institute (2007) included Norilsk in its list of the ten most polluted places on Earth. Although there is no doubt that the problem is rather acute, some statements that have appeared in mass media, such as, 'Within 30 mi (48 km) of the nickel smelter there's not a single living tree' (Walsh 2007), are incorrect.

According to a recent BBC News (2007) report, Norilsk Nikel accepted responsibility for what has happened to the forest, but the company stressed that it was taking action to cut pollution. Voting arranged on a local website (www.norilskinfo.ru) for 2 weeks in January 2008 did not attract much attention; only two of 70 visitors identified local pollution problems as life-threatening.

2.2.2.13 Revda, Russia: Copper Smelter (Color Plates 51–54 in Appendix II)

Location and Environment

Revda (population 61,800; data from 2007) is an industrial town in the Sverdlovsk Region, located on the western slopes of the Middle Ural Mountains, 45 km west of Ekaterinburg (Fig. 2.14). Over 60% of the surrounding territory is covered by southern taiga, now represented mostly by secondary stands co-dominated by Siberian fir and Siberian spruce (please see color plate 52 in Appendix II).

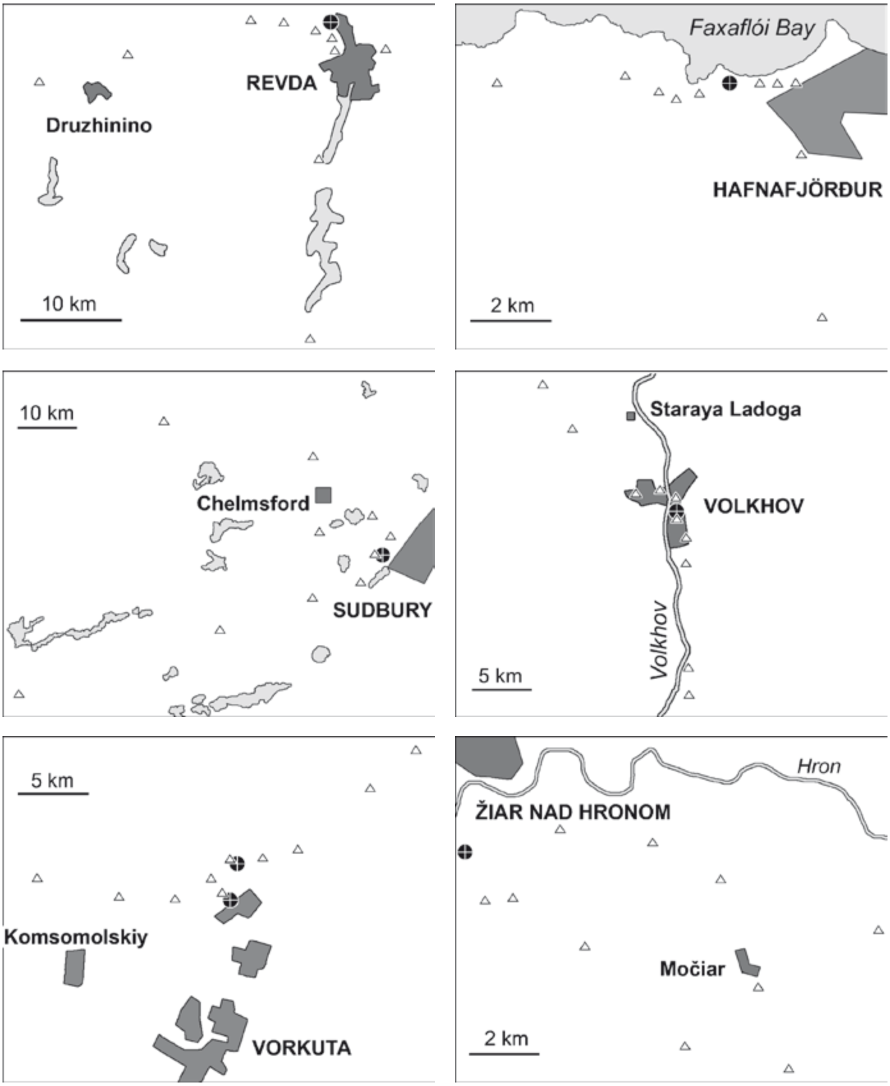
Pre-industrial History

The first settlements on the Revda River, to the south of the recent position of the town, already existed 7–8,000 years ago. However, the territory remained sparsely populated until the beginning of the eighteenth century.

Industrial History

Development of Revda started in 1734 with the launching of an iron foundry. This factory, owned by Akinfij Demidov, produced 3,300–4,900 t of iron annually by the late 1700s. By 1907, production had increased to 16,000 t. In 1897, Revda had 8,000 inhabitants.

The decision by the Soviet government to build a copper smelter between Revda and Pervouralsk was made in 1931. Industrial development started from the building of roads and the railway and constructing a brick factory and wood processing facilities. Town status was acquired in 1935. The concentration mill was launched in 1937 and expanded in 1939. The building of the Middle Ural Copper Smelter started in 1938, and the first copper was produced in 1940. Development of the smelter continued after World War II; it has produced sulphuric acid since 1963 and super phosphate since 1972. Renovation of the smelting facilities began in 1984, and renovation of the shop producing sulphuric acid began in 2004. In 2006, the smelter employed 4,527 workers and produced 95,233 t of copper, 465,015 t of sulphuric acid, and substantial amounts of other chemical products (www.sumz.umn.ru). Revda also hosts iron and non-ferrous processing factories, a brick plant, a mechanical enterprise and several small-scale industries.



Figs. 2.14–2.19 Distribution of study sites (triangles) around investigated polluters (black circles with white cross inside). Names of larger settlements (usually towns) are capitalised. **2.14**, copper smelter in Revda, Russia; **2.15**, aluminium smelter in Straumsvík, Iceland; **2.16**, nickel-copper smelter in Copper Cliff near Sudbury, Canada; **2.17**, aluminium smelter in Volkhov, Russia; **2.18**, power plant and cement factory near Vorkuta, Russia; **2.19**, aluminium smelter in Žiar nad Hronom, Slovakia

Emissions Data

Metallurgy is responsible for 91–99% of all industrial emissions in Revda (Emissions of pollutants in Russia 1966–2006). The contribution of the copper

Table 2.17 Aerial emissions (t) from industrial enterprises at Revda, Russia

Year	Dust	SO_2	CO	NO_x	HF	As	Pb	Cu	Zn
1980	25,100	201,700	21,100	3,100	1,950	–	–	–	–
1981	28,900	143,800	20,200	3,200	1,600	–	–	–	–
1982	26,700	137,400	20,400	1,200	1,400	–	–	–	–
1983	26,799	136,200	20,300	1,200	1,458	–	–	–	–
1984	25,700	142,100	20,500	1,300	1,426	–	913	–	–
1985	25,300	141,100	20,000	1,100	1,340	–	890	–	–
1986	24,500	140,800	19,300	1,200	1,300	900	750	–	–
1987	23,600	139,500	19,300	1,200	1,240	639	565	–	–
1988	23,900	137,800	20,100	1,200	1,202	639	565	–	–
1989	23,500	134,400	20,100	1,200	1,016	639	564	–	–
1990	25,400	131,700	2,600	1,800	–	–	–	–	–
1993	14,600	91,100	2,400	1,100	191	310	401	–	–
1994	13,400	86,000	2,200	1,000	78	287	358	1,163	955
1995	10,400	64,600	2,400	1,100	42	205	292	848	804
1996	10,100	88,400	2,200	1,100	47	172	344	800	766
1997	11,500	86,200	2,000	900	84	216	354	761	903
1998	8,900	64,800	1,700	900	45	121	353	633	812
1999	7,700	58,200	2,200	200	32	116	353	405	828
2000	7,300	56,300	1,600	1,100	32	100	324	337	769
2001	7,300	52,800	1,400	1,000	27	60	302	207	561
2004	3,600	25,300	1,300	900	19	14	160	37	265
2005	3,000	24,300	900	600	20	18	146	49	255

All values were extracted from Emissions of Pollutants in Russia (1966–2006).

Table 2.18 Aerial emissions (t) from the Middle Ural Copper smelter at Revda, Russia

Year	Dust	SO_2	NO_x	HF	As	Pb	Cu	Zn
1980	–	–	–	–	943[a]	1,077[a]	4,400[a]	–
1986	20,910[b]	140,625[b]	470[b]	1,295[b]	908[b]	754[b]	–	–
1987	16,081[b]	139,325[b]	485[b]	1,242[b]	637[b]	565[b]	2,617[b]	1,779[b]
1988	16,110[b]	137,645[b]	485[b]	1,016[b]	639[b]	565[b]	2,918[b]	1,769[b]
1989	16,086[b]	134,089[b]	479[b]	1,011[b]	640[b]	564[b]	2,610[b]	1,753[b]
1990	15,967[b]	130,827[b]	477[b]	1,014[b]	620[b]	546[b]	2,532[b]	1,701[b]
1991	–	95,370[b]	375[b]	935[b]	455[b]	450[b]	1,480[b]	1,505[b]
1992	–	95,369[b]	361[b]	375[b]	353[b]	449[b]	1,479[b]	1,173[b]
1995	–	63,628[c]	–	–	–	292[c]	842[c]	791[c]
2003	–	29,600[c]	–	–	–	217[c]	88[c]	326[c]

All the values were extracted from publications that refer to the copper smelter as to the sole polluter.
Data sources:
[a] Zyrin et al. (1986).
[b] Yusupov et al. (1999).
[c] E. Vorobeichik (personal communication, 2006).

smelter is difficult to evaluate due to a shortage of reliable information. Therefore, we have grouped all the data into two tables, one reporting emissions from all industrial enterprises of Revda (Table 2.17) and the other referring to the copper smelter only (Table 2.18).

Pollution Loads and the Extent of the Contaminated Territory

Ambient concentrations of pollutants in Revda have been monitored since 1972; the peak reported values were 8.70 mg/m^3 of dust in 1975, 10.2 mg/m^3 of SO_2 in 1973, 0.65 mg/m^3 of NO_x in 1978, and 0.47 mg/m^3 of HF in 1975 (Emissions of pollutants in Russia 1966–2006). In the mid-1970s, an average multiyear ambient concentration of SO_2 within 2 km from the smelter was 2.04 mg/m^3 (Fimushin 1979).

From 1987 to 1989, annual depositions of sulphur and nitrogen in Revda were 11,700 and 1,200 kg/km^2, respectively (Vasilenko et al. 1991). Maximum annual depositions of metals (presumably in the early 1990s) were 1,044 kg/km^2 of copper, 443 kg/km^2 of zinc, 244 kg/km^2 of lead and 13 kg/km^2 of cadmium (Kaigorodova & Vorobeichik 1996). In the late 1990s, SO_2 concentrations 2 km from the smelter reached 15 mg/m^3 (Koroleva & Shavnin 2000). The pollution impact caused soil acidification (the lowest recorded pH = 2.9). Peak reported metal concentrations in soils were 14,000 mg/kg of copper (Sataeva 1992), 4,194 mg/kg of zinc, 2,348 mg/kg of lead, and 80 mg/kg of cadmium (Vorobeichik 2003a, b; Kozlov & Zvereva 2007a).

The first detailed survey of environmental contamination and ecosystem damage around Revda, with maps showing concentrations of metals in soil and plants, was performed in the early 1980s (Zyrin et al. 1986). The overall extent of the 'damaged' area was between 21 km^2 (soil 'damage') and 57 km^2 (visible vegetation damage) (Figs. 3.5 and 3.11 in Zyrin et al. 1986). Soil contamination by copper exceeded the regional background over 686 km^2 (Zyrin et al. 1986). Data from 1986–1991 provide a similar estimate, suggesting a doubling of pollutant deposition (relative to the regional background) over 700 km^2 (Prokacheva et al. 1992). Measurements from 1995–1998 revealed that soil contamination by metals expanded over 1,800 km^2 (Vorobeichik 2003b).

Habitat Transformation due to Human Activity

Development of the industrial barrens around Revda (please see color plates 53 and 54 in Appendix II) is tentatively dated to the early 1950s (Kozlov & Zvereva 2007a); their extent in the early 1960s was outlined by Tarchevskij (1964). Importantly, a part of this barren zone (to 2 km east and between 0.5 and 1.5 km southeast) had (at least until 1945) been used for agricultural purposes. Thus, the industrial barrens in this area differ from the industrial barrens located south and north to northeast of this polluter, which have developed directly from declining coniferous forests (Tarchevskij 1964). In the early 1980s, the extent of the industrial barrens was between 3.7 km^2 (as estimated from vegetation damage) and 5 km^2 (as estimated from soil erosion) (Zyrin et al. 1986, Figs. 3.5 and 3.11). In the 2000s, the industrial barrens occupied less than 3 km^2 (Kozlov & Zvereva 2007a).

In the mid-1970s, visible forest damage by pollution occurred over approximately 415 km^2 (Fimushin 1979). We are not aware of any publications reporting the overall recent extent of forest damage. However, severe forest damage in the late 1990s was recorded over 90 km^2 (Fomin & Shavnin 2001).

Brief History of Environmental Research

Exploration of the environmental effects caused by emissions of the copper smelter at Revda started in the early 1960s (Tarchevskij 1964). Researchers from the Institute of Plant and Animal Ecology (Ekaterinburg) contributed the most to the exploration of this impact zone. The history of environmental research at this institution has recently been outlined by Vorobeichik (2005), who also listed the most important publications related not only to Revda but also to other polluters in the Ural region. Several monographs are entirely (Vorobeichik et al. 1994; Yusupov et al. 1999; Bezel et al. 2001) or partly (Bezel 1987, 2006; Bezel et al. 1994, 2001; Shebalova & Babushkina 1999; Vasfilov 2002) based on environmental data collected around Revda. As a result, the impact zone of the copper smelter at Revda is one of the best explored polluted regions in the world; most functional and taxonomic groups of terrestrial biota have been studied there. The most detailed information has been accumulated on pollution-induced changes in soil quality and microbiological activity (Kovalenko et al. 1997; Shebalova & Babushkina 1999; Vorobeichik 1995, 2002, 2007), soil-dwelling invertebrates (Vorobeichik 1998; Ermakov 2004), mycorrhizal fungi (Veselkin 2004a, b) and xylotrophic basidiomycetes (Bryndina 2000), epiphytic lichens (Mikhailova & Vorobeichik 1999; Scheidegger & Mikhailova 2000; Mikhailova 2007), structure and productivity of plant communities (Khantemirova 1996; Goldberg 1997; Shavnin et al. 1999; Trubina 2002), and the diversity and breeding success of birds (Belskii & Lyakhov 2003; Eeva et al. 2006a) and small mammals (Lukyanova 1990; Mukhacheva 1996, 2007). Importantly, a substantial number of data were analysed in terms of dose–effect relationships, and this analysis demonstrated non-linearity in ecosystem responses, i.e., the existence of threshold pollution load at which the ecosystems undergo a rapid transition between two alternative, relatively stable, states (Vorobeichik et al. 1994; Vorobeichik & Khantemirova 1994; Vorobeichik 2003b). Unfortunately, the vast majority of the results are published in Russian, largely in low-circulation books.

Perception of the Environmental Situation

Although the Russian version of Wikipedia (ru.wikipedia.org) and several popular publications (Kočí 2006) claim the existence of a local ecological catastrophe, we did not find signs of specific public anxiety.

2.2.2.14 Straumsvík, Iceland: Aluminium Smelter (Color Plates 55–57 in Appendix II)

Location and Environment

The smelter is located on the northwestern coast of the Reykjanes Peninsula, 12 km southwest of Reykjavik, and 2 km outside of Hafnarfjörður (Hafnarfjord), the third largest settlement in Iceland (population 25,000; data from 2007) and one of the nation's largest fishing centres (Fig. 2.15). Although the area was presumably covered by birch woodlands when Iceland was first settled 1,100 years ago, currently the smelter is surrounded by a flat, open, treeless landscape (please see color plates 56 and 57 in Appendix II). Specific vegetation coverings of the lava fields near the smelter are classified as grasslands, grassy heaths, and heathlands (Magnússon & Thomas 2007).

Pre-industrial History

Cove Straumsvík, located between the smelter and the former farm Straumur, south of the town Hafnarfjörður, was a harbour and a trading post frequented by German traders during the late Middle Ages. Hafnarfjörður was first named in the medieval 'Book of Settlements', and the earliest reports of voyages to Hafnarfjörður date from the end of the fourteenth century. The settlement attained official municipal status in 1908.

Industrial History

In 1966, the Icelandic Parliament permitted the construction of the aluminium smelter. Construction started in 1967, and the smelter was launched in 1969. Soon the smelter at Straumsvík became a major polluter. For about a decade it was the largest industrial firm in Iceland without any pollution control, until dry cleaning was set up in the late 1970s. HF cleaning efficiency remained about 93% until the late 1980s, when it increased to 99.3% (G. M. Gíslason 2008, personal communication).

The initial production was 33,000 t of aluminium annually; since then, the smelter has been expanded four times, and its capacity increased to 162,000 t in the late 1990s (US Geological Survey 1999) and 179,000 t in 2006. Recently, the smelter staff included 500 people. A small harbour was constructed for the import of raw materials and the export of aluminium. Electricity is supplied by the hydroelectric power station at Burfell. From the beginning of operations to the end of 2006, the plant has produced 3.7 million tons of aluminium. The area of Straumsvík also houses a steel smelter, an asphalt factory, and several small-scale industries (Magnússon 2002, Magnússon & Thomas 2007).

Emissions Data

Data from 1980–2006 are summarised in Table 2.19. Tómasson and Thormar (1998) also reported aerial emissions of CF_4, which decreased from 62 t in 1988 to 3 t in 1996.

Pollution Loads and the Extent of the Contaminated Territory

Ambient concentrations of fluorides within 1 km of the smelter from 1977 to1980 exceeded 0.001 mg/m^3 (re-calculated for F) in 12 samples out of 16, with a peak

Table 2.19 Aerial emissions (t) from the aluminium smelter at Straumsvík, Iceland

Year	SO_2	Dust	Fluorine (total)
1980	1,444	2,408	1,137
1981	1,447	2,408	1,044
1982	1,577	1,401	681
1983	1,436	330	270
1984	1,489	552	536
1985	1,311	514	499
1986	1,473	588	477
1987	1,587	719	575
1988	1,485	428	576
1989	1,441	625	568
1990	1,480	290	433
1991	1,546	401	–
1992	1,558	70	95
1993	1,610	49	122
1994	1,680	50	139
1995	1,543	48	160
1996	–	68	122
1998	2,435[a]	162[a]	146[a]
1999	2,696[a]	100[a]	106[a]
2000	2,722[a]	129[a]	97[a]
2001	2,524[a]	177[a]	108[a]
2002	2,638[a]	160[a]	127[a]
2003	2,496[a]	167[a]	113[a]
2004	2,391[a]	173[a]	98[a]
2005	2,477[a]	151[a]	111[a]
2006	2,395[a]	141[a]	106[a]

Non-referenced data after Tómasson and Thormar (1998, Table 2.1; reprinted, in a modified form, with permission from Natturfræðingurinn).
[a]Environment and Food Agency of Iceland (personal communication, 2008)

value of 0.094 mg/m^3. Concentrations of sulphur dioxide exceeded 0.050 mg/m^3 in five samples out of nine, with a peak value of 0.090 mg/m^3 (Thormar & Jóhannesson 1981; cited after Gíslason & Helgason 1989). In 1994–1995 at Hvaleyrarholt (2.5 km northeast of Straumsvík), the average concentration of HF was 0.00005 mg/m^3 (peak value of 0.00049 mg/m^3), and that of SO_2 was 0.00088 mg/m^3 (peak value of 0.0107 mg/m^3) (Tómasson & Thormar 1998). Current measurements at this location are available at www.vista.is.

Fluorine analyses in vascular plants and mosses suggested that in 1971, the contaminated zone extended 10–11 km from the smelter; the peak concentration of 558 mg/kg was recorded at a distance of 900 m in the moss *Hylocomium splendens* (Comission on Fluorine Tolerance Limits 1971, cited after Gíslason & Helgason 1989). Concentrations of fluorine in grass have steadily declined since the late 1980s, following a decrease in emissions (Tómasson & Thormar 1998).

From 2000–2005, the extent of the metal-contaminated territory was less than 3 km from the smelter. The increased levels of arsenic (three times the regional background), nickel (five times the regional background) and sulphur (10% over the regional background) in mosses were attributed to the smelter, while 1.5–5 fold increases in cadmium, copper, lead and zinc most likely resulted from other industrial activities (Magnússon 2002). By 2005, the concentrations of nickel and sulphur near the smelter decreased relative to 2000, although they remained higher than in more distant localities (Magnússon & Thomas 2007).

Habitat Transformation due to Human Activity

Substantial changes in vegetation structure, including the replacement of declining mosses and lichens by crowberry (*Empetrum nigrum*), a decrease in plant species richness, and an increase in the area of exposed rock surfaces, were detected close to the smelter (300 m). Sites 2 km away were unaffected in terms of vegetation structure (Kristinsson 1998).

Brief History of Environmental Research

Very few environmental studies have been conducted in the vicinity of the smelter, and most of them concern concentrations of pollutants in ambient air and plants (Gíslason & Helgason 1989; Magnússon 2002, Magnússon & Thomas 2007). To our knowledge, a survey of plant communities by Kristinsson (1998) is the only publication reporting changes in terrestrial biota near the aluminium smelter at Straumsvík.

Perception of the Environmental Situation

Discussion of environmental issues has increased considerably in Iceland during 2000s, and Alcoa (the owner of the Straumsvík smelter) is listed as 'The Nature Killer' (www.savingiceland.org). Plans to increase production of aluminium at Straumsvík to 400,000 t were blocked by local people with a referendum (88 deciding votes). Inhabitants of Hafnarfjörður voted against the expansion of the smelter in particular to prevent further hydroelectric development because a valuable area of Thjórsárver in the Central Highlands of Iceland would be partially inundated by a hydroelectric reservoir to supply sufficient electricity for the expanded Straumsvík smelter. Moreover, expansion of the smelter would reduce the area available for housing development in Hafnarfjörður (G. M. Gíslason 2008, personal communication). Even after a referendum, the people of Hafnarfjörður continued to protest, including by means of public actions such as blocking the gates of the smelter (Krater 2006).

2.2.2.15 Sudbury, Canada: Nickel-Copper Smelters (Color Plates 58–60 in Appendix II)

Location and Environment

Greater Sudbury (population 157,857; data from 2006) is a city in Northern Ontario, about 400 km North of Toronto (Fig. 2.16). It was created in 2001 by amalgamating the cities and towns of the former Regional Municipality of Sudbury.

Sudbury lies in the Great Lakes–St. Lawrence forest region. One part of this region was originally covered by stands of red and white pine (*Pinus resinosa* and *P. strobus*). In another part, white pine was mixed with hardwoods such as sugar maple (*Acer saccharum*) and yellow birch (*Betula alleghaniensis*). Although the pre-industrial state of vegetation within the severely degraded area was not described, stumps and vestiges hint at a mosaic of pine forests on the slopes and white cedar (*Thuja occidentalis*) swamps in many of the depressions.

Pre-industrial History

The area around the current location of Sudbury has been populated for at least 7,000 years. In 1824, the Hudson Bay Company established a fur-trading post near what was later to become Sudbury. Originally named Sainte-Anne-des-Pins, the community developed from a small lumber camp in McKim Township. Lumbering started in 1872 and until 1927 remained the dominant business, despite the emergence of the mining industry in the 1880s.

Industrial History

The first roast yard and smelter were set up in Copper Cliff in 1888, and open-bed roasting continued until 1929. The development of smelting facilities at Copper Cliff started in 1903, and the present smelter has been operating since 1930. An additional smelter was built in Coniston in 1913 (closed in 1972), and the third smelter was opened at Falconbridge in 1928. In 1972, the famous Super Stack, 381 m in height, was built at the Copper Cliff smelter. For more historical details, consult Gunn (1995) and Sudbury Area Risk Assessment (2008); statistics on annual metal production at the INCO and Falconbridge smelters and refineries are summarised in the Canadian Minerals Yearbooks (www.nrcan.gc.ca).

Emissions Data

By 1949, more than 900,000 t of sulphur dioxide had been discharged into the atmosphere (Linzon 1958; cited after Costescu & Hutchinson 1972). In the early 1960s, Sudbury's copper-nickel complex with three smelters (listed above) was one of the largest point sources of industrial pollution, contributing approximately 4% of global sulphur dioxide emissions. The peak emission of sulphur dioxide (2,560,000 t) was recorded in 1960, and since then it has steadily declined to approximately 700,000 t in the 1980s and 200,000 t in the 2000s, with 183,000 t in 2006. Annual data on SO_2 emission for the years 1960–1994 (total for all Sudbury smelters and separately for the Falconbridge smelter) were published by Gunn (1995, Figs. 4.6 and A4.2). Data for the years 1970–2006 are available on the INCO website (www.inco-cc-smelter.com). Average emissions from four different sources at the Copper Cliff smelter and the Falconbridge smelter from 1973–1981, along with annual data for SO_2 and particulate emissions through the superstack, were reported by Chan and Lusis (1985); separate data for the Copper Cliff and Falconbridge smelters were published by Pollution Probe (2003).

Data on particulate emissions are less detailed. It was estimated that they totalled approximately 35,000 t annually in the 1960s, approximately 10,000 t in 1976–1977, and approximately 3,500 t annually in the mid-1980s (Freedman & Hutchinson 1980a; Allum & Dreisinger 1987). Dust emissions during the period from 1973–1981 contained 1,800 t of iron, 700 t of copper, 500 t of nickel, 200 t of lead and 125 t of arsenic (Chan & Lusis 1985).

Recently, emissions of sulphur dioxide, total particulate matter, and some metals from smelting at Copper Cliff for the period 1930–2003 were summarized by Bouillon (2003; cited after Sudbury Area Risk Assessment 2008). Since the available information greatly differs in both spatial (different emission sources included) and temporal resolution (data are shown for different time periods), we do not provide a summary table for Sudbury emissions. This work remains to be done by someone who has access to the archives of the Sudbury smelters.

Pollution Loads and the Extent of the Contaminated Territory

The long-term emission impact resulted in soil acidification (the lowest reported pH was 2.0) and severe contamination by metals. The peak reported concentrations in soils were 9,700 mg/kg of copper, 12,300 mg/kg of nickel, 336 mg/kg of zinc, and 92 mg/kg of lead (Hutchinson & Whitby 1974; Hazlett et al. 1983; Dudka et al. 1995).

By the 1960s, sulphur dioxide adversely affected 5,300 km^2 (Dreisinger & McGovern 1970); increased concentrations of nickel and copper were reported up to 50–70 km from the nearest smelter (Hutchinson & Whitby 1974; Freedman & Hutchinson 1980a). The territory with average mean ambient concentrations of sulphur dioxide over 0.01 ppm (equivalent to approximately 0.013 mg/m^3), as estimated from lichen surveys, decreased from 480 km^2 in 1968 (LeBlanc et al. 1972) to 230 km^2 in 1978 (Beckett 1984) due to an emissions decline and construction of the superstack.

Habitat Transformation due to Human Activity

Development of industrial barrens on hilltops close to the roast yards started prior to 1920 (Allum & Dreisinger 1987). A combination of lumbering, forest fires, smelter emissions and soil erosion created a barren landscape that, prior to the beginning of reclamation, occupied approximately 100 km^2. This ‘moonscape’ was surrounded by 360 km^2 of open woodland dominated by stunted and coppiced trees of canoe birch (*Betula papyrifera*), red maple (*Acer rubrum*) and Northern red oak (*Quercus rubra*) (Winterhalder et al. 2001). In total, approximately 1,000 km^2 was classified as smelter-damaged lands, of which barren lands (please see color plate 59 in Appendix II) occupied 61.6 km^2 in 1970 and 35.7 km^2 in 1989. This difference can be attributed to both emissions reduction (that allowed vegetation to recover naturally) and implementation of the land reclamation program (McCall et al. 1995).

Brief History of Environmental Research

Environmental deterioration in the Sudbury area is perfectly documented (Courtin 1994; Gunn 1995; Munton 2002). Historically, the studies focussed on freshwater ecosystems (Gunn 1995; Nriagu et al. 1998; Yan et al. 2003), while terrestrial biota received less attention. On the other hand, Sudbury is one of only a few contaminated sites where development of metal-tolerant races of grasses (Cox & Hutchinson 1980) and mosses (Beckett 1986) has been properly documented.

Studies of forest damage had already started in the 1940s, but their first results were not widely available. Pioneering works by Gorham and Gordon (1960a, b), followed by those by Freedman and Hutchinson (1980a, b), describing both contamination and changes in vegetation structure are among the most cited data sources in the domain of pollution ecology. However, responses of terrestrial biota to pollution are properly documented only for soil microbiota (Anand et al. 2003) and vegetation (mosses: Gignac 1987; lichens: LeBlanc et al. 1972; Beckett 1984; Cox & Beckett 1993; vascular plants: Gorham & Gordon 1960a; Amiro & Courtin 1981; Freedman & Hutchinson 1980b). Although the studies were initiated to evaluate the pollution impact on local forests, no quantitative (i.e., suitable for meta-analysis) plant growth data have been published.

Perception of the Environmental Situation

Home of one of the world's largest metal smelting complexes, Sudbury for many years was widely known as a wasteland. However, this reputation has changed recently, with air pollution control efforts and implementation of the largest and most successful municipal land restoration program (Gunn 1995).

In the late 1970s, combined private, public, and commercial interests initiated an unprecedented 'regreening' effort (Gunn 1995). In 1992, Sudbury was one of 12 world cities given the Local Government Honours Award at the United Nations Earth Summit to recognise the city's community-based environmental reclamation strategies (en.wikipedia.org). The reclamation effort is described on several web sites (e.g., www.cyberbeach.net, www.inco.com). The emissions problem, although not as acute as it was, is still of importance to the local people, as can be seen from discussions on a local web site (www.northernlife.ca).

2.2.2.16 Volkhov, Russia: Aluminium Smelter (Color Plates 61–63 in Appendix II)

Location and Environment

Volkhov (Volkhovstroy from 1933 to1940) is a small (population 45,800; data from 2007) industrial town in the Leningrad Region, situated on the Volkhov River, 120 km east of St. Petersburg (Fig. 2.17). The region belongs to the mid-taiga zone, with mixed forests that were earlier dominated by Norway spruce.

Pre-industrial History

Volkhov is located only 12 km south of Staraya Ladoga (Ladoga before the eighteenth century), the oldest Russian settlement in this part of the country (known from the eighth century). Coniferous forests were repeatedly cut and burned to clear the area for agricultural use. They have now generally been replaced with deciduous forests formed by white and silver birches, black alder, and European aspen, as well as by meadows and agricultural landscapes (please see color plates 62 and 63 in Appendix II).

Industrial History

The building of the Volkhov hydroelectric plant was completed in 1926, and in 1932, the first Soviet aluminium plant (constructed with the assistance of the French company Ale Forge Comarg) was launched nearby to take advantage of local bauxite from the Tikhvin deposit. Volkhov acquired town status in 1933. In 1941, soon after the German attack on the USSR, equipment from the smelter was dismantled and sent to the Ural region. Production at Volkhov was restored in 1946, and in the 1950s the plant started integrated processing of nepheline ores transported from the Kola Peninsula. In the 1960s, facilities for production of various chemicals (including soda, potassium carbonate, sulphur acid, and super phosphate) were built to utilise the by-products of aluminium production. Cement and alumina production were suspended in 1995, and super phosphate production was restructured during the same year.

Data on the annual production of 45,000 t of aluminium in the late 1990s (US Geological Survey 1999) seem overestimated; other data sources reported an output of 24,000 t in 1994, 21,000 t in 2001, and 23,500 t in 2006 (Boltramovich et al. 2003; www.sual.ru). Since 2004, the smelter has been owned by SUAL Ltd., which in 2007 became a part of RUSAL Ltd., the world's largest producer of aluminium. Employment decreased from 1,417 in 2001 (Boltramovich et al. 2003) to 514 in 2006 (www.sual.ru).

The town also hosts chemical and cement enterprises. Volkhov has a large railway junction, and mooring and cargo handling facilities on the river that provide access to the St. Petersburg and Murmansk sea ports.

Emissions Data

To our knowledge, emissions data for the Volkhov aluminium smelter have only rarely been estimated. However, the smelter is responsible for a substantial part of the total emissions of sulphur dioxide and nitrogen oxides at Volkhov, and for the entire emission of fluorine (Table 2.20). Along with these data, emissions of 105 t of insoluble fluorides, 227 t of sulphuric acid, and 54 t of SO_3 were reported in 1990 (Ministry of the Environment of Finland 1991a).

Pollution Loads and the Extent of the Contaminated Territory

Ambient concentrations of pollutants in Volkhov have been monitored since 1970; the peak reported values were 6.30 mg/m^3 of dust in 1975, 4.00 mg/m^3 of SO_2 in 1974, and 2.66 mg/m^3 of HF in 1974. Importantly, high concentrations of HF (0.19–0.21 mg/m^3) were recorded up to 2 km, and concentrations of soluble fluorides ranging from 0.08 to 0.10 mg/m^3 were recorded up to 15 km from the smelter in 1971 (Emissions of pollutants in Russia 1966–2006). These concentrations are much lower than in the mid-1950s, when up to 30 mg/m^3 of SO_2 was sometimes observed (Kijamov 1959).

An analysis of fluorine in unwashed common birch leaves was conducted at 24 sites in 1989 and at 12 sites in 1994. The peak concentration from 1989 was around 1,000 mg/kg; in 1994, the concentrations of fluorine were only 10–40% of those recorded in 1989. The fluorine-contaminated area extended approximately 4 km north and 15 km south of the smelter (Kozlov & Zvereva 1997, and unpublished, 1994). The area contaminated by fluorine in the late 1980s covered 62 km^2, and that contaminated by sulphur covered 280 km^2 (Isachenko et al. 1990); however, the quality of the data behind this estimation remains questionable. On the other hand, the data from the period 1986–1991 suggest a doubling (relative to the regional background) of pollutant deposition over 195 km^2 (Prokacheva et al. 1992).

Habitat Transformation due to Human Activity

The severely contaminated area is densely populated, and plant communities are affected by urbanisation, recreation, and agriculture (please see color plate 63 in Appendix II). It therefore seems impossible to attribute any particular changes in vegetation structure to the effects of pollution.

Table 2.20 Aerial emissions (t) from industrial enterprises at Volkhov, Russia

Year	Dust	SO_2	CO	NO_x	HF
1971	–	8,750	–	–	730
1972	–	8,750	–	–	730
1973	–	10,950	–	–	730
1974	–	10,950	–	–	730
1975	–	10,950	–	–	730
1978	9,300	4,600	–	300	240
1979	9,300	4,600	2,300	800	330
1980	9,400	2,600	2,800	900	280
1981	8,900	2,500	2,500	800	222
1982	8,100	2,500	2,800	900	400
1983	9,400	2,900	3,200	1,100	369
1984	7,500	3,000	3,900	900	410
1985	6,700	2,900	2,400	800	320
1986	6,000	3,800	2,300	1,100	360
1987	5,000	3,600	2,100	1,200	250
1988	6,200	3,600	2,100	1,200	–
1989	4,900	3,000	2,000	1,100	378
1990	4,100	2,700	1,200	800	375
	1,816[a]	1,818[a]	1,318[a]	296[a]	162[a]
1991	2,800	2,900	1,900	900	238
1992	2,856[b]	2,388[b]	1,644[b]	–	253[b]
1993	2,300	2,600	1,500	600	133
1994	1,700	1,400	1,400	400	22
1995	1,400	2,900	1,100	300	7
1996	300	1,300	1,200	200	18
1997	200	1,300	900	100	22
1998	200	1,500	1,200	300	16
1999	200	1,600	1,300	300	16
2000	700	1,300	1,500	300	19
2001	719[b]	556[b]	1,600	200	16
	800	600			
2002	2,308[b]	938[b]	1,400	400	16
	2,400	1,500			
2003	2,400	1,500	1,400	400	15
2004	2,600	1,100	1,800	300	26
2005	2,000	1,000	3,100	300	24

Non-referenced values were extracted from Emissions of Pollutants in Russia (1966–2006).
Other data sources:
[a] Ministry of the Environment of Finland (1991a), data refer to the aluminium plant only.
[b] HELCOM (2004), data refer to the aluminium plant only.

Brief History of Environmental Research

Our team started collecting environmental data for bioindication purposes in 1986 and continued monitoring birch-feeding insect herbivores until 2005. However, the information collected in the course of this research remains largely unpublished, except for the data on needle longevity of the Norway spruce (Kozlov 1991), densities of birch-feeding leaf rollers (Kozlov 1991), and abundancies of several groups of flies (Zvereva 1994; Kozlov & Zvereva 1997). We are not aware of any other pollution-related research conducted in this region.

Perception of the Environmental Situation

Extensive health problems (respiratory diseases, fluorosis) had already been reported in the mid-1950s (Kijamov 1959), but their public perception remains unknown. Over the past decades, international concern about pollution in Volkhov (www.pollutedplaces.org) has been much larger than just a local concern. Volkhov had been identified as a 'hot spot' in terms of pollution (mostly discharge of wastewater; www.blacksmithinstitute.org) by the early 1990s, and measures taken by the smelter had positive effects on environmental quality by 2002 (HELCOM 2004). Voting arranged on a Volkhov website (63clan.ru) for 2 weeks in January 2008 did not attract much attention; only three of 82 visitors identified local pollution problems as life-threatening.

2.2.2.17 Vorkuta, Russia: Power Plant and Cement Factory (Color Plates 64–67 in Appendix II)

Location and Environment

The industrial city of Vorkuta (population 90,100; data from 2002) is located in the northwestern Russian tundra (Fig. 2.18), within the permanent permafrost zone, 80 km north of the treeline formed by Siberian spruce. The topography in the region is relatively flat, with elevation varying from 100 m above sea level in the deepest river valleys to 250 m atop the smooth hills. Shrub tundra dominated by dwarf birch (*Betula nana*) is the most common vegetation type, associated with better drained and slightly elevated sites. Depressions are occupied by willow-dominated (*Salix glauca, S. phylicifolia*, *S. lanata*), often paludified, vegetation (please see color plate 66 in Appendix II). A detailed description of the pre-industrial state of the plant communities is given by Rebristaya (1977).

Pre-industrial History

Before the 1930s, the territory was only sparsely populated by aboriginal people subsisting on reindeer herding and hunting.

Industrial History

The Vorkuta region is the largest industrial centre in the tundras of European Russia. It consists of the main city and more than ten subcentres located near coal mines and other industrial units. The city and the first coal mines were established in the 1930s.

The population increased from 30,000 in the early 1950s to over 180,000 in the 1960s, to 216,000 in 1991, and then declined to 127,500 by 2005. For a detailed account of the early industrial development and the use of forced labour, consult Negretov (1977).

The two main air pollutant sources are the Vorkuta cement factory (established in 1950) and the coal-fired power plant (TEZ-2, established in 1956); both are located about 15 km north of the town of Vorkuta. However, their emissions are included in the total emissions of Vorkuta in government reports (Emissions of pollutants in Russia 1966–2006).

Emissions Data

Atmospheric pollution in the area surrounding Vorkuta is mainly associated with dust from open coal mines, emissions from the power plant and cement factory, and burning of waste rock near the coal mines (Table 2.21). Contributions from two

Table 2.21 Aerial emissions (t) from industrial enterprises at Vorkuta, Russia

Year	Dust	SO_2	CO	NO_x
1975	175,200	51,100	34,700	–
1978	107,300	41,800	13,800	11,700
1979	103,500	54,000	26,700	12,000
1980	141,200	47,000	25,200	8,200
1981	135,700	34,000	18,900	7,200
1982	90,700	35,400	4,100	5,600
1983	91,500	43,900	4,000	5,500
1984	108,800	47,000	4,500	4,900
1985	102,700	41,500	4,500	3,400
1986	67,300	41,100	3,500	2,500
1987	62,800	41,400	4,200	4,600
1988	64,100	44,200	3,900	4,600
1989	118,500	46,300	16,600	5,500
1990	128,700	46,400	18,000	5,500
1991	131,800	47,500	17,700	5,800
1992	130,667[a]	50,442[a]	16,235[a]	6,572[a]
1993	111,600	47,500	13,600	6,800
1994	93,500	45,300	11,000	7,400
1995	85,500	46,300	14,100	7,800
1996	79,000	44,100	13,100	7,400
1997	72,100	36,900	10,000	7,300
1998	58,300	36,400	9,400	7,200
1999	58,200	39,900	9,300	7,200
2000	57,900	38,700	9,300	6,900
2001	53,200	33,600	8,600	6,900
2002	53,200	33,600	8,600	6,900
2003	35,000	34,200	7,300	5,900
2004	33,300	33,000	7,100	7,000
2005	26,800	32,300	5,500	6,900

Non-referenced values were extracted from Emissions of Pollutants in Russia (1966–2006).
Other data sources:
[a] Solovieva et al. (2002, and personal communication, 2008).

power plants and the cement factory to local aerial emissions in the late 1980s-early 1990s were 53–56% and 32–34%, respectively (Emissions of pollutants in Russia 1966–2006). Data from 1999–2000 (Tables 2.22 and 2.23) demonstrated that one of the power plants (TEZ-2) is responsible for two thirds of the sulphur dioxide emissions in the Vorkuta region (summarised in Table 2.21). Annual emissions of SO_2 from the two power plants ranged from 37–39,000 t in 1994–1996 (Getsen 2000). Peak emissions from the cement factory reached 60,000 t in the late 1980s (Regional Committee of Nature Protection at Vorkuta, personal communication 2001).

Pollution Loads and the Extent of the Contaminated Territory

Ambient concentrations of pollutants in and around Vorkuta have been monitored since 1974; the peak reported values were 2.70 mg/m^3 of dust in 1978, 1.70 mg/m^3 of SO_2 in 1975, and 0.36 mg/m^3 of NO_x in 1978 (Emissions of pollutants in Russia 1966–2006).

The peak concentrations of dust measured in snow in the mid-1970s suggests an annual deposition rate of approximately 1,000 t/km^2 (Kuliev & Lobanov 1978); values from the late 1990s are about 300 t/km^2 (Getsen 2000). Deposition of calcium-containing dust caused strong alkalisation near the polluters, with soil pH ranging from 6.7 to 8.9 (Getsen et al. 1994), while the soil pH outside of the impacted territory varied from approximately 5 to less than 4.5 (Virtanen et al. 2002). From 1987 to 1989, annual depositions of sulphur and nitrogen in Vorkuta were 1,400 and 700 kg/km^2, respectively (Vasilenko et al. 1991). Pollution caused a strong increase in the soil concentration of strontium (up to 25 times higher than in background regions), along with moderate (two to ten times above the background) increases in zinc, lead, iron, cadmium and chromium concentrations (Krasovskaya 1996).

In the 1970s, smoke from the local polluters was visually observed up to 50 km away. A characteristic smell was detected up to 30 km away, and the presence of cement dust was recorded up to 25 km from the factory (Kuliev & Lobanov 1978). During the period 1986–1991, a doubling of pollutant deposition (relative to the regional background) was recorded for 3,000 km^2 around Vorkuta and adjacent

Table 2.22 Aerial emissions (t) from the cement factory at Vorkuta, Russia

Year	Dust	SO_2	NO_x	HF
1999	18,887	393	300	6
2000	19,115	415	318	6

Unpublished data received from the Regional Committee of Nature Protection at Vorkuta.

Table 2.23 Aerial emissions (t) from the power plant 'TEZ-2' at Vorkuta, Russia

Year	Dust	SO_2	NO_x
1999	22,698	26,900	4,122
2000	21,832	25,072	3,932

Unpublished data received from the Regional Committee of Nature Protection at Vorkuta.

settlements (Prokacheva et al. 1992). At the end of the 1990s, the local gradient in deposition of alkaline ash extended to 25–40 km, with increased concentrations of Ca, Ba, Sr and other alkaline earth metals recorded within approximately 30 km from Vorkuta (Walker et al. 2003a, b). Satellite image analysis (Landsat TM, from 31 July 1988) suggests that the effects of pollution on vegetation are detectable for 600–900 km^2, of which 150–200 km^2 are strongly affected by pollution (Virtanen et al. 2002).

Habitat Transformation due to Human Activity

Substantial changes in terrestrial ecosystems around Vorkuta are caused by a combination of different disturbances, including pollution, coal mining, sand and gravel mining for building purposes, the use of track vehicles, and agriculture (mostly pasture) (Druzhinina 1985). The relative importance of other kinds of disturbances is expected to increase with the decline of pollution (Virtanen et al. 2002; Walker et al. 2006).

Brief History of Environmental Research

Studies on the pollution impact on terrestrial ecosystems around the industrial complex of Vorkuta are scarce, and they are mostly published in Russian (for the list, consult Getsen 2000). Studies from 1976–1978 (Kuliev 1977, 1979; Kuliev & Lobanov 1978) revealed the extent of the pollution impact by analysing the concentration of particles in snow and related these to changes in vegetation structure (in particular, a decline in lichens, accompanied by increases in moss and grass cover) and increased growth of several plants. Studies from the 1990s are summarised in the collection of scientific papers on bioindication (Getsen et al. 1996). A review is given by Virtanen et al. (2002).

Perception of the Environmental Situation

Although Walker et al. (2006) concluded that 'Vorkuta's inhabitants perceived air pollution as the primary environmental threat', we did not find signs of specific public anxiety in local webpages.

2.2.2.18 Žiar nad Hronom, Slovakia: Aluminium Smelter (Color Plates 68–70 in Appendix II)

Location and Environment

Žiar nad Hronom (Svätý Kríž nad Hronom until 1955) is a small (population 19,750; data from 2005) industrial town situated on the northern bank of the river Hron, 150 km northeast of Bratislava (Fig. 2.19). The entire mountainous region belongs to the western Carpathians, with altitudes ranging 300–700 m above sea level. The original vegetation surrounding the polluter (below 600 m above sea level) was oak-beech and beech forest (please see color plates 69 and 70 in Appendix II).

Pre-industrial History

Although the region was populated long ago, the first written reference to Svätý Kríž dates to 1237. During the Middle Ages, Svätý Kríž was a toll-collecting town on an important trade route. In the early 1950s, it was a village of 1,400 people.

Industrial History

Construction of the aluminium plant began in 1951, and production of primary aluminium from bauxite ore by electrolysis was launched in 1953; production of anode matter started in 1954. The coal-fired power plant (a source of both sulphur dioxide and heavy metals) was built in 1956, and a second aluminium electrolysis plant was built in 1958. Additional facilities were built in 1967, and a new heating plant has operated since 1986. In 1985, the company running the aluminium plant started a capital expenditure program to invent modern smelting technology. SLOVALCO, founded in 1993, took over construction of the partly built new smelter and ancillary facilities. Production of aluminium reached 60,000 t in 1966, about 110,000 t annually in the late 1990s, and 176,000 t in 2006 (Maňkovská & Steinnes 1995; US Geological Survey 1999; Maňkovská & Kohút 2002). In the 2000s, the smelter employed between 600 and 700 people (www.slovalco.sk). Recently, metallurgy has formed the basis of local economy.

Emissions Data

Before effective filters were installed, production resulted in the emission of fly ash with high contents of heavy metals and fluorides (gaseous hydrogen fluoride and fluoride minerals such as cryolite), particles of aluminium oxide, sulphur dioxide, and many other substances. Accurate emission records are available starting from 1990 (Table 2.24). The smelter also emitted fluorine-containing dust (from 18 t in 1997 to 0.2 t in 2007: www.slovalco.sk). In the 1990s, the production process was gradually updated, and the closing of the old smelter in 1996 resulted in a reduction of dust emissions. The company also implemented the Environmental Remediation Program (www.slovalco.sk).

Pollution Loads and the Extent of the Contaminated Territory

In the early 1970s, annual deposition of fluorine exceeded 1,000 kg/km^2 up to 2.2 km south of the polluter (Hajdúk 1974), and soils within 16 km^2 contained over 200 mg/kg

Table 2.24 Aerial emissions (t) from aluminium smelter and associated power plant at Žiar nad Hronom, Slovakia

Year	Dust	SO_2	CO	NO_x	HF
1958–1959	–	–	–	–	1,022[a]
1960–1966	–	–	–	–	1,096[a]
1966	–	4,723[a]	–	–	–
1967–1973	–	–	–	–	657[a]
1973	–	11,315[a]	–	–	–
1974–1975	–	–	–	–	563[a]
1975	–	9,606[a]	–	–	–
1990	1,580	6,556	840	810	848
1991	1,718	5,557	932	788	809
1992	1,859	3,879	706	616	557
1993	718	3,555	892	596	364
1994	303	3,168	975	588	319
1995	317	1,943	951	360	326
1996	253	2,373	11,160	378	114
1997	195	2,595	10,603	389	60
	98[b]	1,009[b]	10,499[b]	39[b]	42[b]
1998	177	2,267	10,589	321	58
	97[b]	1,009[b]	10,499[b]	41[b]	40[b]
1999	193	2,651	8,503	486	34
	119[b]	1,511[b]	8,439[b]	230[b]	32[b]
2000	186	2,477	7,960	584	30
	115[b]	1,178[b]	7,887[b]	293[b]	28[b]
2001	190	2,431	7,937	577	30
	118[b]	1,176[b]	7,865[b]	295[b]	28[b]
2002	88[b]	1,293[b]	10,220[b]	403[b]	22[b]
2003	95[b]	1,334[b]	11,618[b]	474[b]	23[b]
2004	104[b]	1,107[b]	13,010[b]	541[b]	24[b]
2005	146[b]	1,310[b]	12,994[b]	689[b]	46[b]
2006	104[b]	1,324[b]	12,956[b]	565[b]	10[b]
2007	98[b]	1,326[b]	12,942[b]	559[b]	9[b]

Non-referenced values after ŽSNP, a.s. (personal communication).
Other data sources:
[a] Sobocky (1977), the annual emissions of HF are averaged for several years.
[b] www.slovalco.sk, data refer to aluminium smelter only.

of fluorine (Kontrišová 1980, Fig. 2.11). The contaminated area approached 500 km^2 (Maňkovská & Steinnes 1995; Krištín & Žilinec 1997). The polluted region was subdivided into zones with different levels of environmental contamination by Maňkovská (1979) and Kontrišová (1980). By the early 2000s, a statistically significant increase in fluorine concentrations over the regional background was detected only within the most polluted zone (61 km^2); however, other zones were still distinguished on the basis of sulphur concentrations (Maňkovská & Kohút 2002). According to another data source, the content of water soluble fluorine in soils in the early 1990s exceeded the sanitary limit (10 mg/kg) for 37 km^2 (Andersen 2000), i.e., within approximately 3.5 km from the smelter.

Habitat Transformation due to Human Activity

The pollution impact did not cause deforestation; however, the signs of pollution damage are easily recognisable in forests located close to the smelter (please see color plate 70 in Appendix II). The proportion of dying trees reached 32% near the polluter, compared to 4.4% in a distant (background) site (Cicák & Mihál 1996). In 1990, heavily damaged stands were observed up to 3 km from the smelter (Bucha & Maňkovská 2002).

Brief History of Environmental Research

The surroundings of Žiar nad Hronom are among the most contaminated areas of the Slovak Republic (Kellerová 2005). The adverse effects of air pollution on forests had already been detected in the late 1950s (Štefančík 1995), and since then, the accumulation of pollutants (inorganic: Maňkovská & Steinnes 1995; Wilcke & Kaupenjohann 1998; Maňkovská & Kohút 2002; polycyclic aromatic hydrocarbons: Wilcke et al. 1996), soil acidification (Löffler 1983; Wilcke & Kaupenjohann 1998) and biotic responses to pollution have been described. Most studies were forestry-oriented, documenting forest vitality (Cicák & Mihál 1996), the occurrence of mycorrhizatl and parasitic fungi (Cicák & Mihál 1996; Mihál & Bučinová 2005), and damage by herbivorous insects (Šušlík & Kulfan 1993; Kulfan et al. 2002). Plant diversity (Hajdúk 1974) as well as abundance, species richness and the breeding success of birds declined near the polluter (Feriancová-Masárová & Kalivodová 1965a, b; Newman 1977; Krištín & Žilinec 1997, and references therein). Data on mammals are restricted to reports on fluorosis in roe deer (*Capreolus capreolus*) (Hell et al. 1995).

A recent decrease in emissions has already resulted in a lower accumulation of pollutants in the foliage of forest trees (Maňkovská 2001, 2004) and in a steady improvement of forest vitality (Bucha & Maňkovská 2002).

Perception of the Environmental Situation

Soon after the launch of the smelter, the pollution problem became extremely acute for the inhabitants of the small village of Horné Opatovice, located less than 1 km from the smelter. The emissions first killed bees, then caused the death of cattle and trees, and worsened health conditions of the inhabitants. Although scientific data on this environmental disaster have not been disclosed, the government of the Czechoslovak Socialist Republic decided to abolish the village in 1960, and this name disappeared from official maps in 1969. Inhabitants (1,380 people living in 228 houses) were mostly relocated to Žiar nad Hronom. However, after reconstruction of the smelter in 1995 and the subsequent emissions decline, pollution is not perceived as a life-threatening problem by local people (J. Kulfan 2008, personal communication).

2.3 Study Sites and General Sampling Design

We have adopted a uniform sampling design for all investigated impact zones. Around each polluter, we selected ten study sites, grouped in two blocks (transects) of five, located in two different directions from the polluter (Figs. 2.2–2.19). The sites are coded by a transect number followed by the site number, with site 1 being the closest to and site 5 the farthest from the polluter.

Deviations from this sampling scheme occurred near Monchegorsk and Žiar nad Hronom. In the impact zone of the Monchegorsk smelter, which was the focus of our research for decades, we chose 17 sampling sites (Fig. 2.10) due to the practical impossibility of collecting all the data (mostly related to plant vigour) from the same set of ten sites; however, each individual analysis is based on ten sites only. Moreover, in this impact zone, we were forced to select both controls to the south of the polluter due to an overlap between the northern part of the impact zone of Monchegorsk smelter with the southern part of the impact zone of the iron ore processing factory in Olenegorsk. In the impact zone of the aluminium plant situated at Žiar nad Hronom, attribution of the study sites to two transects is somewhat arbitrary (Fig. 2.19), since the mountain relief, forestry and agriculture substantially restricted the extent of areas suitable for establishment of study sites.

Two impact zones include more than one point polluter. The smelter at Nikel and ore-roasting plant at Zapolyarnyy are located 25 km apart, and their impact zones overlap substantially (Tømmervik et al. 2003; Kozlov & Zvereva 2007a). Similarly, pollution at Norilsk is imposed by three plants located 5–10 km apart. Therefore, two transects selected in these impact zones start from different polluters (Figs. 2.12 and 2.13). We have chosen to consider the Copper Cliff smelter at Sudbury, Canada, as the sole polluter, since the Coniston smelter located nearby was closed in 1972, and the Falconbridge plant emitted into the ambient air about ten times less SO_2 and about 10–50 times less metal than the Copper Cliff smelter (Pollution Probe 2003).

We started selection of study sites from surveys of all available ecological and environmental information. In particular, at this stage we made a decision on the approximate location of our most distant study sites (5 to 96 km from the polluter), taking into account both the extent of the impact zone under study and its overlap with the impact zones of other polluters. Our intention was to establish the most distant study sites at localities representing the regional background in terms of pollution load. At this stage, we also made a preliminary decision on the type of plant community to be explored.

In the course of the reconnaissance work (1–2 days, depending on the size of the impact zone and road network), we usually visited 15–30 localities potentially suitable for establishment of our study sites. Whenever possible, we explored study sites used by other researchers who had been working in these impact zones earlier. In the course of this reconnaissance work, we made pilot observations on the types of plant communities, stand age and composition (for forested habitats), the occurrence of plant species to be sampled for vitality indices, approximate levels of the pollution impact (evaluated, e.g., by needle longevity in conifers), and disturbances other than the pollution impact (e.g., fellings, fires, recreation). This information was summarised in the form of a table and used to make an optimal selection of study sites. Some pictures taken from the sites not selected for detailed survey, included in the colour section of this book, are labelled as taken at additional sites.

The positions of study sites (Tables 2.25–2.42) were located using GPS. As a rule, all data were collected within 50 m from the point located using GPS; under specific circumstances, such as rarity of one of the selected plant species, some samples were collected up to 100 m from the central point of the study site. At the time of the first visit, we photographed each study site from its approximate central point toward the main compass directions.

Whenever possible, we collected the data over several sampling sessions (Table 2.43); collection of some data over 2 or more years allowed us to account for the repeatability of measurements (discussed in Chapters 3–7). However, due to financial limitations and logistic constrains, two of our impact zones (around Norilsk and Bratsk) were visited only once, and therefore the amount of information collected from these areas is lower than from other (repeatedly visited) study areas. We were unable to measure chlorophyll fluorescence around Sudbury and Vorkuta and soil respiration around Vorkuta.

Data collection was performed by the same team. M. Kozlov collected the data in all impact zones except for Vorkuta; V. Zverev collected the data in all impact zones except for Vorkuta and Sudbury; E. Zvereva collected the data around Harjavalta, Kandalaksha, Monchegorsk, Nikel, Straumsvík, Volkhov and Vorkuta.

Table 2.25 Location of study plots and concentrations of pollutants in the impact zone of power plant at Apatity, Russia

	Plot position				Pollutant concentrations, mg/kg (mean ± SE)[a]	
Plot code	Latitude (N)	Longitude (E)	Altitude, m a.s.l.	Distance from polluter, km	Fe	Sr
Polluter	67°35′55″	33°25′26″	160	0	–	–
1–1	67°35′52″	33°24′54″	160	0.4	45.0 ± 3.2	30.0 ± 3.9
1–2	67°36′36″	33°24′00″	160	1.6	47.8 ± 5.5	20.0 ± 2.3
1–3	67°37′06″	33°22′23″	170	3.1	32.5 ± 6.0	33.2 ± 6.5
1–4	67°37′47″	33°19′46″	160	5.3	18.8 ± 1.2	86.2 ± 6.6
1–5	67°38′22″	33°17′11″	150	7.4	16.0 ± 1.6	37.8 ± 3.2
2–1	67°36′02″	33°26′35″	150	0.9	32.5 ± 1.2	22.8 ± 4.2
2–2	67°35′26″	33°27′44″	160	1.9	40.2 ± 4.3	17.2 ± 2.4
2–3	67°35′08″	33°28′57″	190	2.9	31.8 ± 6.0	10.8 ± 2.3
2–4	67°34′59″	33°30′19″	190	3.9	17.8 ± 1.2	14.2 ± 2.1
2–5	67°34′57″	33°33′02″	190	5.7	11.7 ± 1.7	49.3 ± 12.4

[a] In leaves of speckled alder, *Alnus incana* (four samples per site; collected in 1992); meta-analyses are based on correlations with iron.

Table 2.26 Location of study plots and concentrations of fluorine in the impact zone of aluminium smelter at Bratsk, Russia

Plot code	Plot position			Distance from polluter, km	Fluorine concentrations, mg/kg (mean ± SE)[a]
	Latitude (N)	Longitude (E)	Altitude, m a.s.l.		
Polluter	56°07′44″	101°27′10″	380	0	–
1–1	56°09′00″	101°26′19″	340	1.6	97.2 ± 7.2
1–2	56°08′17″	101°30′31″	400	3.6	52.1 ± 21.5
1–3	56°12′13″	101°37′23″	520	13.0	21.7 ± 4.8
1–4	56°20′15″	101°39′51″	460	27.0	13.4 ± 6.6
1–5	56°35′22″	101°31′35″	400	56.0	2.3 ± 0.1
2–1	56°07′40″	101°29′56″	420	1.8	283.2 ± 68.8
2–2	56°06′00″	101°26′09″	480	2.6	35.3 ± 5.2
2–3	56°05′13″	101°12′00″	400	16.0	11.8 ± 1.9
2–4	55°54′00″	101°05′41″	520	30.0	4.5 ± 0.4
2–5	55°34′50″	101°06′49″	460	65.0	3.6 ± 0.8

[a] In leaves of white birch, *Betula pubescens* (two samples per site; collected in 2002).

Table 2.27 Location of study plots and concentrations of pollutants in the impact zone of nickel-copper smelter at Harjavalta, Finland

Plot code	Plot position			Distance from polluter, km	Pollutant concentrations, mg/kg (mean ± SE)[a]	
	Latitude (N)	Longitude (E)	Altitude, m a.s.l.		Ni	Cu
Polluter	61°19′11″	22°07′16″	30	0	–	–
1–1	61°19′40″	22°07′05″	30	0.93	315.8 ± 38.2	27.2 ± 5.7
1–2	61°19′31″	22°06′28″	30	1.0	903.8 ± 184.7	38.8 ± 6.7
1–3	61°20′13″	22°05′23″	25	2.6	58.2 ± 6.0	6.0 ± 1.9
1–4	61°20′44″	22°03′53″	20	4.2	70.4 ± 8.8	4.8 ± 1.2
1–5	61°23′47″	21°52′21″	25	15.8	20.4 ± 11.7	3.2 ± 0.9
2–1	61°19′14″	22°07′57″	30	0.6	196.4 ± 18.9	39.0 ± 3.5
2–2	61°19′05″	22°08′11″	30	0.8	242.2 ± 11.1	42.8 ± 3.3
2–3	61°18′44″	22°08′57″	30	1.7	154.6 ± 22.0	21.6 ± 4.4
2–4	61°17′42″	22°11′26″	50	4.6	47.8 ± 3.2	7.8 ± 1.6
2–5	61°15′15″	22°18′36″	35	12.5	22.4 ± 2.8	6.6 ± 1.2

[a] In leaves of goat willow, *Salix caprea* (five samples per site; collected in 1999); meta-analyses are based on correlations with nickel.

Table 2.28 Location of study plots and concentrations of pollutants in the impact zone of fertilizing factory at Jonava, Lithuania

Plot code	Plot position			Distance from polluter, km	Pollutant concentrations, mg/kg (mean ± SE)[a]		
	Latitude (N)	Longitude (E)	Altitude, m a.s.l.		Sr	Zn	Ni
Polluter	55°05′02″	24°19′36″	35	0	–	–	–
1–1	55°04′25″	24°19′21’″	39	1.2	28.0 ± 1.5	95.6 ± 12.5	1.51 ± 0.17
1–2	55°03′46″	24°18′60″	72	2.4	13.0 ± 2.7	176.9 ± 37.0	0.87 ± 0.10
1–3	55°02′38″	24°13′43″	69	7.7	18.4 ± 1.5	96.1 ± 1.2	1.82 ± 0.28
1–4	55°01′40″	24°10′38″	55	11.4	13.1 ± 3.2	175.9 ± 47.8	1.53 ± 0.25
1–5	54°57′40″	24°01′47″	80	24.3	21.7 ± 1.7	183.6 ± 4.8	2.51 ± 0.28
2–1	55°05′00″	24°18′51″	33	0.8	13.4 ± 1.4	153.4 ± 39.7	1.36 ± 0.05
2–2	55°05′56″	24°21′55″	69	3.0	35.5 ± 10.4	64.7 ± 21.9	1.27 ± 0.33
2–3	55°06′32″	24°25′31″	88	6.9	14.3 ± 0.2	88.3 ± 10.0	0.86 ± 0.04
2–4	55°08′59″	24°27′47″	69	11.4	37.9 ± 7.4	287.1 ± 32.5	2.44 ± 0.33
2–5	55°10′58″	24°34′04″	48	18.9	11.4 ± 1.1	157.0 ± 28.7	2.73 ± 0.32

[a] In leaves of common birch, *Betula pendula* (three samples per site; collected in 2005); meta-analyses are based on correlations with strontium.

Table 2.29 Location of study plots and concentrations of fluorine in the impact zone of aluminium smelter at Kandalaksha, Russia

	Plot position			Distance from polluter, km	Fluorine concentrations, mg/kg (mean ± SE)	
Plot code	Latitude (N)	Longitude (E)	Altitude, m a.s.l.		1998[a]	2002[b]
Polluter	67°11′43″	32°25′51″	80	0	–	–
1–1	67°12′20″	32°26′25″	90	1.2	26.9 ± 9.5	99.4 ± 22.0
1–2	67°12′57″	32°26′09″	110	2.3	15.1 ± 2.4	117.4 ± 20.0
1–3	67°13′47″	32°24′52″	150	3.9	15.0 ± 2.1	54.9 ± 1.6
1–4	67°14′57″	32°25′35″	140	6.0	15.6 ± 5.3	44.0 ± 8.6
1–5	67°16′53″	32°27′12″	130	9.7	8.0 ± 2.0	27.2 ± 3.6
2–1	67°11′27″	32°26′11″	70	0.6	21.1 ± 3.7	142 ± 20.5
2–2	67°10′40″	32°25′24″	80	2.0	19.2 ± 5.3	84.1 ± 9.2
2–3	67°09′39″	32°26′56″	60	3.9	–	36.6 ± 11.8
2–4	67°08′42″	32°26′01″	40	5.6	13.3 ± 2.7	20.9 ± 2.7
2–5	67°09′45″	32°07′44″	85	13.6	–	6.9 ± 1.2

[a] In needle of Scots pine, *Pinus sylvestris* (five samples per site; collected in 1998).
[b] In leaves of mountain birch, *Betula pubescens* ssp. *czerepanovii* (two samples per site; collected in 2002); meta-analyses are based on correlations with data of 2002.

Table 2.30 Location of study plots and concentrations of pollutants in the impact zone of copper smelter at Karabash, Russia

	Plot position			Distance from polluter, km	Pollutant concentrations, mg/kg (mean ± SE)[a]	
Plot code	Latitude (N)	Longitude (E)	Altitude, m a.s.l.		Cu	Zn
Polluter	55°28′03″	60°12′07″	360	0	–	–
1–1	55°29′00″	60°13′17″	380	2.2	164.6 ± 5.2	1,107 ± 50
1–2	55°30′01″	60°15′35″	340	5.2	45.8 ± 3.3	327 ± 33
1–3	55°31′42″	60°20′08″	320	10.8	37.8 ±10.8	312 ± 82
1–4	55°36′44″	60°25′19″	280	21.3	13.9 ± 1.7	260 ± 92
1–5	55°42′47″	60°28′17″	260	32.2	14.3 ± 2.2	173 ± 67
2–1	55°27′13″	60°12′20″	330	1.6	238.2 ± 19.9	1,282 ± 200
2–2	55°26′18″	60°13′05″	330	3.4	129.2 ± 22.3	517 ± 54
2–3	55°24′39″	60°08′55″	330	7.1	51.9 ± 2.5	455 ± 162
2–4	55°13′19″	60°09′00″	320	27.5	15.9 ± 1.8	265 ± 52
2–5	55°06′47″	59°57′11″	420	42.5	11.3 ± 1.4	175 ± 43

[a] In leaves of *Betula pendula* (three samples per site; collected in 2003); meta-analyses are based on correlations with copper.

Table 2.31 Location of study plots and concentrations of pollutants in the impact zone of iron pellet plant at Kostomuksha, Russia

	Plot position				Pollutant concentrations, mg/kg (mean ± SE)[a]	
Plot code	Latitude (N)	Longitude (E)	Altitude, m a.s.l.	Distance from polluter, km	Cu	Fe
Polluter	64°38′52″	30°45′07″	200	0	–	–
1–1	64°39′04″	30°43′55″	200	1.0	4.40 ± 0.09	1,296 ± 19
1–2	64°41′42″	30°45′15″	200	5.3	4.01 ± 0.45	441 ± 14
1–3	64°42′31″	30°52′26″	170	9.0	3.88 ± 0.18	224 ± 22
1–4	64°45′14″	30°47′50″	190	12.0	4.24 ± 0.49	805 ± 190
1–5	64°49′46″	30°42′36″	150	20.4	4.75 ± 0.58	592 ± 158
2–1	64°38′52″	30°45′40″	190	0.5	5.08 ± 0.49	3,758 ± 160
2–2	64°37′53″	30°43′08″	200	2.4	8.06 ± 3.08	1,278 ± 249
2–3	64°37′06″	30°39′46″	190	5.4	4.10 ± 0.56	354 ± 57
2–4	64°34′26″	30°53′19″	170	10.5	6.27 ± 1.38	170 ± 20
2–5	64°29′49″	31°07′32″	150	24.6	2.80 ± 0.10	95 ± 7

[a] In leaves of white birch, *Betula pubescens* (three to five samples per site; collected in 2003); meta-analyses are based on correlations with iron.

Table 2.32 Location of study plots and concentrations of pollutants in the impact zone of copper smelter at Krompachy, Slovakia

	Plot position				Pollutant concentrations, mg/kg (mean ± SE)[a]	
Plot code	Latitude (N)	Longitude (E)	Altitude, m a.s.l.	Distance from polluter, km	Cu	Ni
Polluter	48°55′20″	20°52′56″	370	0	–	–
1–1	48°55′45″	20°52′52″	540	0.7	15.6 ± 1.98	4.30 ± 0.53
1–2	48°56′09″	20°50′43″	500	3.0	13.9 ± 1.93	2.30 ± 0.55
1–3	48°56′35″	20°49′33″	410	4.7	11.2 ± 0.91	2.53 ± 0.19
1–4	48°55′11″	20°46′49″	460	7.4	6.43 ± 0.61	0.79 ± 0.17
1–5	48°55′54″	20°43′10″	430	12.0	16.6 ± 7.73	2.62 ± 0.64
2–1	48°55′14″	20°54′04″	450	1.5	35.6 ± 17.8	2.24 ± 0.47
2–2	48°54′30″	20°53′16″	460	1.7	11.1 ± 1.46	1.88 ± 0.28
2–3	48°53′47″	20°53′16″	730	2.9	8.77 ± 0.12	3.11 ± 0.44
2–4	48°54′33″	20°56′32″	390	4.6	6.50 ± 1.13	2.97 ± 0.51
2–5	48°48′38″	21°00′25″	550	15.4	7.03 ± 0.24	1.75 ± 0.41

[a] In leaves of European beech, *Fagus sylvatica* (three samples per site; collected in 2002); meta-analyses are based on correlations with copper.

Table 2.33 Location of study plots and concentrations of pollutants in the impact zone of nickel-copper smelter at Monchegorsk, Russia

	Plot position				Pollutant concentrations, mg/kg (mean ± SE)[b]	
Plot code	Latitude (N)	Longitude (E)	Altitude, m a.s.l.	Distance from polluter,[a] km	Ni	Cu
Polluter	67°55′15″	32°50′18″	140	0	–	–
1–1	67°56′04″	32°49′08″	180	1.6	237.1 ± 25.2	86.5 ± 13.2
1–2	67°58′07″	32°52′29″	140	5.0	145.8 ± 24.0	67.5 ± 7.3
1–3	67°59′37″	32°54′57″	160	8.1	(72.2 ± 5.5)	(20.2 ± 1.9)
1–4	68°00′59″	32°57′03″	180	11.1	44.8 ± 5.4	16.9 ± 1.5
1–5	68°02′20″	33°00′53″	180	14.6	(32.8 ± 4.5)	(10.4 ± 0.7)
2–1	67°54′49″	32°48′30″	190	1.1	(119.2 ± 8.6)	(56.2 ± 5.7)
2–2	67°52′59″	32°46′40″	210	4.3	318.0 ± 29.4	134.3 ± 14.2
2–3	67°51′58″	32°47′50″	260	5.7	586.8 ± 92.7	323.9 ± 60.5
2–4	67°51′01″	32°48′10″	240	7.5	315.8 ± 39.1	147.2 ± 32.8
2–5	67°48′03″	32°46′56″	140	13.0	163.3 ± 6.4	67.4 ± 4.78
2–6	67°46′36″	32°47′45″	200	15.6	131.6 ± 5.2	80.3 ± 3.8
2–7	67°45′31″	32°48′29″	210	17.5	(88.8 ± 5.2)	(38.0 ± 4.9)
2–8	67°40′39″	32°49′27″	220	26.7	52.3 ± 3.3	28.0 ± 1.6
2–9	67°38′21″	32°45′00″	170	31.1	23.8 ± 2.1	13.2 ± 1.0
2–10	67°34′38″	32°32′54″	140	39.7	19.3 ± 0.4	10.0 ± 0.4
2–11	67°34′46″	33°35′22″	220	49.5	(12.0 ± 2.3)	(9.6 ± 0.4)
2–12	67°32′16″	33°57′52″	240	64.0	5.9 ± 0.3	5.7 ± 0.3

[a] Measured from the nearest smokestack.
[b] In leaves of mountain birch, *Betula pubescens* ssp. *czerepanovii* (three samples per site; collected in 2003, except for values in parentheses that are each based on five samples collected in 1993); consult Kozlov (2005a) for comparability of contamination data; meta-analyses are based on correlations with nickel.

Table 2.34 Location of study plots and concentrations of pollutants in the impact zone of aluminium smelter at Nadvoitsy, Russia

	Plot position				
Plot code	Latitude (N)	Longitude (E)	Altitude, m a.s.l.	Distance from polluter, km	Fluorine concentrations, mg/kg (mean ± SE)[a]
Polluter	63°52′50″	34°15′50″	100	0	–
1–1	63°53′15″	34°15′53″	100	0.8	60.7 ± 2.0
1–2	63°53′44″	34°14′04″	110	2.2	59.4 ± 10.8
1–3	63°54′31″	34°12′55″	110	3.9	25.8 ± 2.5
1–4	63°55′44″	34°07′47″	100	8.5	14.8 ± 4.7
1–5	64°01′45″	34°04′12″	110	19.1	11.2 ± 4.2
2–1	63°53′08″	34°16′34″	100	0.8	85.8 ± 20.7
2–2	63°52′31″	34°17′39″	100	1.6	65.4 ± 3.8
2–3	63°52′47″	34°20′40″	100	4.0	15.8 ± 0.2
2–4	63°52′28″	34°24′12″	90	6.9	12.4 ± 3.1
2–5	63°51′30″	34°29′58″	80	11.8	8.6 ± 0.8

[a] In leaves of white birch, *Betula pubescens* (two samples per site; collected in 2004).

Table 2.35 Location of study plots and concentrations of pollutants in the impact zone of nickel-copper smelter at Nikel (Polluter 2) and ore-roasting plant at Zapolyarnyy (Polluter 1), Russia

	Plot position				Pollutant concentrations, mg/kg (mean ± SE)[a]	
Plot code	Latitude (N)	Longitude (E)	Altitude, m a.s.l.	Distance from the nearest polluter, km	Ni	Cu
Polluter 1	69°24′25″	30°47′49″	160	0	–	–
1–1	69°24′40″	30°47′51″	140	0.5	366.3 ± 53.7	175.3 ± 23.8
1–2	69°25′30″	30°52′45″	70	3.8	67.9 ± 3.9	23.5 ± 1.3
1–3	69°26′50″	31°02′10″	90	10.4	36.0 ± 3.7	7.8 ± 0.4
1–4	69°27′46″	31°29′44″	170	28.1	14.8 ± 2.3	6.4 ± 0.2
1–5	69°26′34″	31°56′42″	160	45.3	7.5 ± 0.5	5.2 ± 0.6
Polluter 2	69°24′46″	30°14′30″	100	0	–	–
2–1	69°24′42″	30°16′32″	230	1.4	273.3 ± 24.0	139.0 ± 13.2
2–2	69°23′32″	30°10′45″	70	3.4	96.6 ± 9.4	48.9 ± 5.7
2–3	69°21′15″	30°03′11″	90	9.9	47.7 ± 7.0	18.6 ± 2.0
2–4	69°16′14″	30°04′56″	230	17.1	29.2 ± 2.6	16.7 ± 1.8
2–5	69°04′28″	30°12′15″	200	37.8	33.1 ± 2.1	9.4 ± 0.1

[a] In leaves of mountain birch, *Betula pubescens* ssp. *czerepanovii* (five samples per site; collected in 2001); meta-analyses are based on correlations with nickel.

Table 2.36 Location of study plots and concentrations of pollutants in the impact zone of nickel-copper smelters at Norilsk, Russia

	Plot position				Pollutant concentrations, mg/kg (mean ± SE)[a]	
Plot code	Latitude (N)	Longitude (E)	Altitude, m a.s.l.	Distance from the nearest polluter, km	Ni	Cu
Polluter 1	69°19′25″	87°58′20″	220	0	–	–
Polluter 2	69°21′45″	88°08′10″	90	0	–	–
Polluter 3	69°19′00″	88°12′10″	100	0	–	–
1–1	69°20′35″	88°01′20″	120	2.5	133.9 ± 10.6	459.6 ± 37.7
1–2	69°21′55″	87°37′20″	140	14.5	21.5 ± 0.3	31.3 ± 5.5
1–3	69°22′40″	87°20′10″	120	25.9	12.8 ± 1.1	17.8 ± 2.0
1–4	69°23′25″	86°46′50″	70	47.5	6.7 ± 0.6	15.6 ± 1.0
1–5	69°25′00″	86°23′05″	60	64.0	7.6 ± 0.5	10.1 ± 0.9
2–1	69°19′35″	88°18′35″	50	4.0	82.7 ± 14.0	62.1 ± 4.2
2–2	69°21′30″	88°23′20″	40	9.0	53.4 ± 9.8	33.9 ± 5.1
2–3	69°32′40″	88°19′30″	80	21.0	31.0 ± 3.2	22.7 ± 0.8
2–4	69°20′40″	89°00′55″	50	31.8	12.9 ± 1.1	16.1 ± 1.4
2–5	69°28′00″	90°36′00″	50	96.0	2.8 ± 0.4	7.0 ± 1.1

[a] In leaves of woolly willow, *Salix lanata* (three samples per site; collected in 2002); meta-analyses are based on correlations with nickel.

Table 2.37 Location of study plots and concentrations of pollutants in the impact zone of copper smelter at Revda, Russia

	Plot position				Pollutant concentrations, mg/kg (mean ± SE)[a]	
Plot code	Latitude (N)	Longitude (E)	Altitude, m a.s.l.	Distance from polluter, km	Cu	Zn
Polluter	56°51′11″	59°54′06″	360	0	–	–
1–1	56°50′40″	59°52′41″	360	1.7	58.2 ± 1.4	888 ± 183
1–2	56°51′05″	59°49′33″	380	4.6	13.8 ± 1.5	640 ± 156
1–3	56°51′15″	59°46′23″	420	7.8	11.3 ± 0.5	649 ± 110
1–4	56°49′19″	59°34′13″	330	20.5	6.5 ± 0.9	170 ± 16
1–5	56°47′51″	59°25′36″	380	29.7	5.2 ± 0.5	326 ± 56
2–1	56°50′15″	59°54′17″	360	1.7	50.3 ± 8.8	576 ± 104
2–2	56°49′37″	59°54′33″	350	3.0	41.1 ± 5.8	841 ± 130
2–3	56°49′41″	59°59′30″	340	6.2	33.2 ± 10.6	575 ± 40
2–4	56°43′47″	59°53′00″	350	13.8	11.3 ± 2.0	309 ± 77
2–5	56°34′10″	59°52′06″	360	31.7	7.6 ± 0.1	338 ± 33

[a] In leaves of white birch, *Betula pubescens* (three samples per site; collected in 2003); meta-analyses are based on correlations with copper.

Table 2.38 Location of study plots and concentrations of fluorine in the impact zone of aluminium smelter at Straumsvík, Iceland

	Plot position				
Plot code	Latitude (N)	Longitude (W)	Altitude, m a.s.l.	Distance from polluter, km	Fluorine concentrations, mg/kg (mean ± SE)[a]
Polluter	64°02′44″	22°01′39″	15	0	–
1–1	64°02′26″	22°02′17″	15	0.77	24.4 ± 5.0
1–2	64°02′17″	22°02′48″	10	1.26	0.26 ± 0.24
1–3	64°02′10″	22°03′12″	20	1.71	0.81 ± 0.79
1–4	64°02′15″	22°04′19″	20	2.35	1.61 ± 1.51
1–5	64°01′30″	22°07′22″	30	5.19	0.04 ± 0.00
2–1	64°02′54″	22°00′48″	15	0.70	6.0 ± 0.8
2–2	64°02′58″	22°00′28″	15	1.06	4.4 ± 2.4
2–3	64°03′05″	21°59′59″	20	1.51	1.0 ± 0.5
2–4	64°02′20″	21°58′58″	25	2.31	0.9 ± 0.3
2–5	64°00′40″	21°56′35″	85	5.64	0.05 ± 0.02

[a] In leaves of dwarf birch, *Betula nana* (two samples per site; collected in 2002).

Table 2.39 Location of study plots and concentrations of pollutants in the impact zone of nickel-copper smelter at Copper Cliff, Sudbury, Canada

	Plot position				Pollutant concentrations, mg/kg (mean ± SE)[a]	
Plot code	Latitude (N)	Longitude (W)	Altitude, m a.s.l.	Distance from polluter, km	Ni	Cu
Polluter	46°28′36″	81°03′33″	300	0	–	–
1–1	46°30′18″	81°02′37″	315	3.4	192.0 ± 7.4	79.4 ± 6.8
1–2	46°32′02″	81°04′47″	320	6.5	96.2 ± 17.7	35.9 ± 2.6
1–3	46°30′37″	81°12′00″	315	11.4	38.6 ± 5.5	14.4 ± 1.4
1–4	46°37′30″	81°12′43″	300	20.2	20.9 ± 4.2	9.0 ± 0.6
1–5	46°40′37″	81°32′38″	450	43.3	7.8 ± 0.8	21.9 ± 4.3
2–1	46°28′28″	81°04′39″	285	1.4	225.3 ± 9.3	47.7 ± 5.5
2–2	46°26′00″	81°06′28″	280	6.1	180.8 ± 19.2	50.9 ± 1.1
2–3	46°24′34″	81°12′59″	270	14.2	27.0 ± 1.1	10.7 ± 0.6
2–4	46°21′48″	81°24′56″	260	30.1	13.2 ± 1.7	6.1 ± 0.9
2–5	46°15′46″	81°51′24″	210	65.8	4.3 ± 0.3	5.4 ± 0.2

[a] In leaves of canoe birch, *Betula papyrifera* (three samples per site; collected in 2007); meta-analyses are based on correlations with nickel.

Table 2.40 Location of study plots and concentrations of fluorine in the impact zone of aluminium smelter at Volkhov, Russia

	Plot position				
Plot code	Latitude (N)	Longitude (E)	Altitude, m a.s.l.	Distance from polluter, km	Fluorine concentrations, mg/kg (mean ± SE)[a]
Polluter	59°54′38″	32° 21′22″	30	0	–
1–1	59°55′12″	32° 20′46″	30	1.2	38.1 ± 0.9
1–2	59°55′39″	32°19′50″	30	2.0	17.8 ± 2.3
1–3	59°55′40″	32°18′28″	40	3.3	13.0 ± 1.6
1–4	59°56′52″	32°13′37″	40	8.3	5.5 ± 0.2
1–5	59°59′35″	32°10′32″	40	13.7	5.8 ± 0.6
2–1	59°54′31″	32°21′02″	30	0.3	146.1 ± 29.4
2–2	59°53′30″	32°21′48″	30	2.1	54.6 ± 8.4
2–3	59°52′19″	32°21′36″	30	4.4	16.9 ± 0.3
2–4	59°47′32″	32°21′44″	20	13.2	7.2 ± 0.7
2–5	59°46′20″	32°21′38″	20	15.4	6.6 ± 0.5

[a] In leaves of white birch, *Betula pubescens* (two samples per site; collected in 2002).

Table 2.41 Location of study plots and concentrations of pollutants in the impact zone of power plant at Vorkuta, Russia

Plot code	Plot position			Distance from polluter, km	Pollutant concentrations[a] (Mean ± SE), mg/kg	
	Latitude (N)	Longitude (E)	Altitude, m a.s.l.		Cu	Fe
Polluter	67°37′20″	64°05′30″	160	0	–	–
1–1	67°36′30″	64°04′00″	160	0.8	5.44 ± 1.32	71.0 ± 10.4
1–2	67°37′00″	64°02′40″	160	2.0	8.05 ± 0.55	302.3 ± 35.6
1–3	67°36′30″	63°59′35″	160	4.0	7.37 ± 0.41	163.7 ± 7.9
1–4	67°36′45″	63°53′30″	160	8.0	6.73 ± 0.74	74.1 ± 4.3
1–5	67°36′10″	63°45′20″	180	14.0	5.44 ± 1.32	71.0 ± 10.4
2–1	67°37′40″	64°04′30″	140	0.3	8.49 ± 0.26	414.1 ± 46.3
2–2	67°37′00″	64°08′40″	180	2.1	7.56 ± 0.40	248.5 ± 32.9
2–3	67°38′30″	64°12′00″	180	4.6	10.33 ± 0.11	268.3 ± 30.2
2–4	67°40′20″	64°21′30″	200	12.0	7.32 ± 0.41	83.3 ± 7.4
2–5	67°42′25″	64°26′40″	160	17.5	5.72 ± 0.41	79.5 ± 6.3

[a] In leaves of woolly willow, *Salix lanata* (three samples per site; collected in 2001); meta-analyses are based on correlations with iron.

Table 2.42 Location of study plots and concentrations of fluorine in the impact zone of aluminum smelter at Žiar nad Hronom, Slovakia

Plot code	Plot position			Distance from polluter, km	Fluorine concentrations, mg/kg (mean ± SE)[a]
	Latitude (N)	Longitude (E)	Altitude, m a.s.l.		
Polluter	48°34′00″	18°50′50″	250	0	–
1–1	48°33′15″	18°51′20″	350	1.5	79.0 ± 4.7
1–2	48°33′19″	18°51′53″	350	1.7	47.5 ± 3.4
1–3	48°32′40″	18°53′30″	580	4.1	10.0 ± 0.7
1–4	48°31′05″	18°52′40″	680	8.4	5.9 ± 0.4
1–5	48°31′00″	18°57′40″	600	10.0	3.8 ± 0.4
2–1	48°34′17″	18°52′54″	300	2.6	8.3 ± 0.4
2–2	48°34′06″	18°54′53″	440	4.9	4.0 ± 0.1
2–3	48°33′35″	18°56′19″	460	6.7	2.5 ± 0.5
2–4	48°32′05″	18°57′05″	560	8.5	3.1 ± 2.1
2–5	48°32′52″	18°59′38″	390	11.0	1.8 ± 0.2

[a] In leaves of European beech, *Fagus sylvatica* (two samples per site; collected in 2002).

Table 2.43 Data collection timetable

Site	Dates of sampling sessions by study year									
	Prior 1999	1999	2000	2001	2002	2003	2004	2005	2006	2007
Apatity	3–7.7.1992; 9.8.1997	–	–	–	–	–	–	–	**30.7;** 19.8	–
Bratsk	–	–	–	–	**2–4.8**	–	20–25.1	–	–	–
Harjavalta	28.8.1997; 26.8.1998	31.8	–	26.9	**25.8**	–	–	–	7.10	7.11
Jonava	–	–	–	–	–	–	–	**3–5.9**	–	12.10
Kandalaksha	10.6.1998	–	–	15.9	**26.6, 16–17.7**	–	5.8	25.7	12.7	11.7
Karabash	–	–	–	–	–	**23–25.7**	–	–	–	31.8–1.9
Kostomuksha	–	–	–	11–12.9	20.3, **18.7**	–	–	–	21.8	–
Krompachy	–	–	–	–	**2–5.9**	–	6–8.10	–	11.11	–
Monchegorsk[a]	12–14.7.1993; 17.6–6.7.1997	10.7–11.8; 10–13.9	22–27.6	16.6–5.8	**14–20.8**	17.6–2.8; 12–19.10	21–27.8	11.7–20.8	10.7–13.8	–
Nadvoitsy	–	–	–	–	–	–	31.5; **25–27.7**; 25–26.8	23.8	18.6	16.8
Nikel	–	–	–	**17–18.7**	–	11–12.6; 29.6–1.7; 12–13.10	18–19.8	5–7.8	24–26.6; 8–9.8	5–6.7
Norilsk	–	–	–	–	**23–30.7**	–	–	–	–	–
Revda	–	–	–	–	–	**19–21.7**	–	–	–	24–26.8

Straumsvík	–	–	–	–	**11–13.7**	–	–	–	–	30.10–1.11
Sudbury	–	–	–	–	18–19.5	–	–	–	–	**19–21.10**
Volkhov	18.9.1994, 9.9.1998	5.9.	–	–	9.6; **8–9.8;** 11.10	–	–	–	17.6	17.8
Vorkuta	–	–	–	**8–10.7**	–	–	–	–	8–9.7	–
Žiar nad Hronom	–	–	–	–	**29.8–1.9**	–	3–5.10	–	9.11	–

The dates of the principal sampling session (when the majority of the data have been collected) are boldfaced.
[a] In Monchegorsk we also estimated longevity of Scots pine on 12.6.2008.

Although assisting personnel changed with sampling year and impact zone, this was not expected to cause variation in the outcomes of our surveys because all measurements that require specific training were performed by the authors, who conducted training sessions to assure the uniformity of methods across the entire study.

2.4 Environmental Contamination at Study Sites

2.4.1 Sampling and Preservation

As the basic estimate of the pollution load at our study sites we used total concentrations of selected pollutants in unwashed samples of plant leaves. Thus, our samples reflect both root and canopy uptake of pollutants (Kozlov et al. 2000).

Woody plants with large, preferably pubescent, leaves were selected for analyses of pollutants. We sampled white birch (eight impact zones), common birch (2), European beech (2), woolly willow, *Salix lanata* (2), goat willow, *Salix caprea* (1), dwarf birch (1), canoe birch (1), speckled alder (1) and Scots pine (1). Samples were taken from five mature plants randomly selected at each site (the same individuals from which vigour indices were measured; consult Chapter 4), within approximately 25 m from the marked centre of the study plot. One branch with 30–50 shoots was cut at a height of 1.2–1.4 m (except for dwarf birch in Iceland, where the uppermost twig was collected), packed in a plastic bag and transported to the laboratory. The next day after sampling, the leaves were cut by scissors in such a way that the basal parts of petioles and buds were not included in the sample; care was taken to avoid cross-contamination. In birches, only short-shoot leaves (Fig. 5.1) were sampled. Unwashed leaf samples were packed in paper bags, dried for 12–24 h at 80°C, and preserved for analysis. The parts of samples that were not used for our analyses were deposited in the Paljakka Environmental Bank of the Finnish Forest Research Institute.

2.4.2 Analyses

2.4.2.1 Metals

Concentrations of metals in samples from 1992–1993 (from Apatity and Monchegorsk) and from 1999 (from Harjavalta) were determined by X-ray fluorescence (Spectrace 5000 spectrometer, Tractor X-Ray, USA) at St. Petersburg State University, Russia. Samples from 2001–2005 were analysed by ICP (Analist 800, Perkin Elmer, USA) at the Institute of North Industrial Ecology, Apatity, Russia. Samples from 2007 (from Sudbury) were analysed by ICP-OES (IRIS Intrepid II XSP, Thermo Electron Corporation, USA) at the University of Joensuu, Finland.

The quality of the analytical data was checked by replicate analyses of the same samples, both by blind tests with the same analytical procedure in the original laboratory and by comparing the results obtained in different laboratories. For more details on sample preparation, analytical procedures and intercalibrations, consult Kozlov et al. (1995, 2000) and Kozlov (1996, 2005a).

2.4.2.2 Fluorine

Total concentrations of fluorine were determined by Enviroservis, s.r.o., Žiar nad Hronom, Slovakia. Foliar samples were pulverised and dried at 75°C to a constant weight. Each sample was subdivided into two parts that were processed independently, according to internal procedure PP OZP 006 cl. 5.7; the results were averaged for a sample-specific value.

Fluoride concentrations were measured by potenciometry with a fluoride ion selective electrode (Orion model 96-09, Thermo Electron Corporation, USA) in the automatic system SINTALYZER (SINTEF ADR 7034, Trondheim, Norway) and compared to the blank test conducted with a certified reference material GBW07604 (poplar leaves) with a fluoride concentration of 22 ± 4 mg/kg.

2.5 Statistical Approaches

2.5.1 Traditional Analyses

2.5.1.1 Data Inspection and Transformation

Raw data were first inspected for obvious errors. Then distributions of the data were analysed by SAS UNIVARIATE procedure (SAS Institute 2007). Following removal of the identified outliers (usually less than 0.5% of all measurements), the data were averaged by observational units (sensu Kozlov & Hurlbert 2006) and log-transformed whenever necessary.

2.5.1.2 Variation Between Sites

Distributions of individual measurements, or measurements averaged by observational units (sensu Kozlov & Hurlbert 2006), were used to test the null hypothesis, that there were no differences between the ten study sites within the impact zone of a given polluter. This analysis was performed using either ANOVA for normally distributed variables (SAS GLM procedure) or the Kruskal-Wallis test based on X^2 for variables with highly skewed distributions (SAS NPAR1WAY procedure).

Since the later analyses were based on plot-specific values, we chose not to include standard errors or other measures of within-plot variation in the data tables.

2.5.1.3 Test for Non-linearity of Responses

We checked whether second-degree polynomial regression fit the data better than linear regression. These tests were only performed using log-transformed distances as explanatory variables, and only for biotic response variables (i.e., concentrations of pollutants and soil quality indices, except for soil respiration, have been excluded from this analysis). For the data sets where the quadratic model had a significant second-degree component, we compared residual variations for linear and second-degree regression models using *F*-statistics (Motulsky & Christopoulos 2004; web calculator at http://graphpad.com/quickcalcs/AIC1.cfm), with one degree of freedom subtracted from the second-degree regression model to account for the additional parameter.

2.5.1.4 Correlation Analysis

Relationships between response variables and both distance from the polluter and concentration of pollutants (indicated in Tables 2.25–2.42) were explored by correlation analyses (SAS CORR procedure; SAS Institute 2007); correlations with both explanatory variables are reported in all data tables in Chapters 3–7. Logarithmic transformation was applied to the distance data to make them roughly proportional to the deposition of pollutants. As a rule, we calculated the Pearson linear correlation coefficient; however, if the distribution of response variables was highly skewed (e.g., herbivore density data), the Spearman rank correlation coefficient was calculated instead.

2.5.2 Meta-analyses

2.5.2.1 General Approaches

Meta-analysis is a quantitative synthetic research method that statistically integrates results from individual studies to find common trends and differences (Gurevitch & Hedges 2001). This method has been demonstrated to be a much better tool than traditional narrative review for synthesising results from multiple studies with diverse outcomes. Although meta-analysis is becoming increasingly popular in basic ecology, it is relatively rarely applied to integrate field collected environmental data (but see Ruotsalainen & Kozlov 2006; Menzel et al. 2006; Kozlov & Zvereva 2007b; Zvereva et al. 2008; Zvereva & Kozlov 2009).

In this book, we use the meta-analytic approach to summarise collected information, search for general patterns, and identify the sources of variation in changes of structural and functional parameters of terrestrial ecosystems. In general, our approach follows the methodology described by Zvereva et al. (2008). However, in this book we also explore whether correlations with distance and correlations with pollutant concentrations generally yield the same results, and whether contrast between the two most polluted and two control sites is sufficiently informative in comparison with the gradient approach involving ten study sites.

2.5.2.2 Calculation of Effect Sizes

To calculate effect sizes (ESs) based on the gradient approach involving ten study sites, individual correlation coefficients were *z*-transformed and weighed by their sample size. Note that the sign of the correlation coefficient between response variables and distance was changed by multiplying by (−1) to make these data consistent with correlations calculated for concentrations of pollutants; in our database, positive ESs denote an increase in the response variable with an increase in pollution.

Hedge's d (another measure of the ES) was calculated as the difference between the means based on the two most polluted and two control plots divided by the pooled standard deviation.

It should be stressed that the expressions 'positive effect of pollution' and 'negative effect of pollution' used throughout the text should not be perceived as 'beneficial' and 'adverse' effects. These expressions only denote that the parameter under study in polluted site(s) attained higher and lower values than in control site(s), respectively.

2.5.2.3 Overall Effect and Sources of Variation

If not stated otherwise, our analyses are based on ESs calculated from correlations between the measured parameter and the concentration of the selected pollutant (indicated in Tables 2.25–2.42). The mean ESs were calculated and compared using a random effect model with 95% confidence intervals (CIs). If the number of ESs in an individual analysis was seven or less, then we used a bootstrap estimate of the CI.

Separate meta-analyses were conducted for each class of response variables. Pollution was considered to have a statistically significant effect if the 95% CI of the mean effect size did not overlap zero (Gurevitch & Hedges 2001).

Variation in ES among classes of categorical variables was explored for each response variable by calculating between-class heterogeneity (Q_B) and testing it against the X^2 distribution (Gurevitch & Hedges 2001).

All calculations described above were performed using the MetaWin program (version 2.1.4; Rosenberg et al. 2000).

2.5.2.4 Repeatability of Results

When measurements of some index were performed more than once for two or more study areas, we used a meta-analysis to check for repeatability of the observed patterns.

For this analysis, we calculated all pairwise Pearson linear correlation coefficients between site-specific values obtained from the same study area and then calculated ES from these coefficients as described above (Section 2.5.2.2). The mean ESs were calculated and compared using a random effect model. A pattern was considered repeatable if the 95% CI of the mean effect size did not overlap zero.

2.5.2.5 Regression Analysis of Effect Sizes

We applied stepwise regression analysis (SAS REG procedure; SAS Institute 2007) to better understand the sources of variation in the responses of selected structural and functional characteristics of terrestrial ecosystems to pollution. In particular, it was used to estimate the contribution of different geographical (latitude of the polluter's location), climatic (mean July and January temperatures and annual precipitation in the locality) and polluter (emissions of principal pollutants and duration of the impact) characteristics to the variation of the effect size. The distribution of variables was checked, and appropriate transformation (usually logarithmic) was applied whenever necessary.

2.5.3 Significance of Effects

Through the entire book, the presence of an effect means that the effect in question was significant at $P = 0.05$; the absence of an effect means that, for the given test, $P > 0.05$. Sometimes we use expressions such as ‘tended to be’ for effects whose significance approached $P = 0.05$; an actual probability level is always reported in these situations.

2.6 Summary

The selected 18 polluters differ in the type and amount of emissions, as well as in pollution history, climate and type of primary vegetation within the impact zone. Considered together, they are sufficiently representative to reveal general patterns in the effects of industrial polluters on terrestrial ecosystems of temperate to northern regions of the Northern hemisphere. Uniformity in sampling design and proper replication at all hierarchical levels allowed us to decrease the impact of methodology-related variation (which is typical in meta-analyses of published data) on the outcome of the comparative analysis. To study possible causal links between pollution impacts and biotic effects, as well as general patterns and sources of variation, we used a combination of traditional statistical procedures (analysis of variance, correlation and regression analyses) and meta-analyses based on correlations with distances, correlations with pollution loads, and relative differences between the most and least polluted sites.