Microclimate changes along a strong pollution gradient in northern boreal forest zone

M. Kozlov & E. Haukioja
Laboratory of Ecological Zoology, University of Turku, FIN-20014 Turku, Finland
EMail: mikoz@sara.utu.fi, haukioja@utu.fi

Abstract

We monitored air and soil temperatures around the Severonikel smelter in Monchegorsk (Kola Peninsula, Northwestern Russia) in 1992-1996. Soil froze in autumn/winter and thawed in spring earlier in heavily polluted industrial barrens than in unpolluted forests. Spring and summer soil temperatures were highest in industrial barrens. During the growth season, air temperatures in heavily polluted sites were either lower (in cool days) or higher (in warm days) than in unpolluted forests. Daily mean air temperatures along the pollution gradient could be estimated from records of meteorological station in Monchegorsk, measurements of pollution load, and altitudes of the study sites. Pollution affected microclimate mostly by altering habitat characteristics, primarily canopy transparency and structure of ground vegetation cover. Pollution-induced changes in temperature regime may increase, mask or compensate toxic effects of pollutants on plants and animals.

1 Introduction

Although ecological consequences of aerial pollution are reasonably well documented[12], causal links in impact of emissions on terrestrial ecosystems are not well understood. For example, shifts in seasonal development of plants[1, 2, 32, 42] and animals[36] recorded in several pollution gradients may either occur due to direct impact of emissions on study organisms or indicate microclimatic changes in affected habitats. The latter mechanism was suggested for several moth species with 7 to 9 days earlier phenology near the oil refining factory in Byelorussia than at reference sites[6]. However, pollution effects on regional climate are studied quite infrequently[9], and microclimatic changes have not, to our knowledge, been monitored along a strong pollution gradient.

In the course of a field study of mountain birch (*Betula pubescens* subsp. *tortuosa*) around the Severonikel smelter it became evident that pronounced variation in temperature regime among our plots obscures toxic effects of pollution. Because of practical reasons, we were unable to obtain representative temperature records from twenty study sites during the five study years, and monitored temperatures in only a few of them. Therefore we were forced to find out regularities which allow estimation of temperature regime in the remaining sites on the basis of (1) temperature records obtained at the meteorological station in Monchegorsk and (2) habitat characteristics, including measures of topographic factors and pollution-induced disturbances. In this paper, we report air temperatures during the growth season (May to September in our study area) and soil temperatures between growth seasons (October to May) along the Severonikel pollution gradient. Data on the phenology of mountain birch along this gradient will be published elsewhere.

2 Materials and methods

2.1 Study area

The study was conducted near Monchegorsk (Kola Peninsula, Russia; 67°52'N, 32°48'E). This northern taiga region was covered with coniferous forests before the 1930's[7]. Vast quantities of SO_2 and heavy metals, emitted by the Severonikel nickel-copper smelter since 1938, have caused widespread destruction of vegetation and soils, and imposed human-derived environmental gradients around the smelter[20]. Coniferous forests have completely vanished up to 6-10 km south and 5-6 km north of the smelter, and have been replaced by willow- and birch-dominated communities[19, 22]. Areas adjacent to the smelter (ca. 30 km^2) are transformed to industrial barrens[22]. Visible effects of emissions on vegetation have been recorded up to 60-80 km, and measurable traces of pollutants up to 200 km from the smelter[39].

The emissions from Severonikel smelter, besides SO_2 and metal-containing aerosols, also include oxides of C and N, Cl_2, H_2S, and formaldehyde[5]. The spatial distributions of SO_2 and heavy metals followed the same patterns[4] and were similar during the past years[21]. We quantified pollution by mean concentration of Ni in birch foliage during 1991-1996[21].

The study sites, hereafter abbreviated with the distance (km) and direction (N, North; S, South) from the smelter, were located 130-260 m a.s.l. within the following habitats[4, 19, 20, 21, 22]: industrial barrens (1 N, 3 N, 1 S, 7 S, 9 S), birch transitional communities (5 S, 15 S), severely (11 N, 15 N, 20 S) and slightly (29 S, 47 S) damaged coniferous forests. The most distant site (65 S) was situated in an unpolluted spruce forest.

2.2 Data recording

Air temperatures were measured at a height of 0.7-1.5 m above the ground by sheltered recorders. Soil temperatures were measured at a depth of ca 0.15 m; disturbances of the soil and vegetation above the data logger were kept to a minimum. We used HAMSTER (TM) modules (Elpro-buchs ag., Switzerland) in 1992-1994 and TINYTALK (TM) data loggers (Orion Components Ltd., Chichester, UK) in 1995-1996, one recorder per site. Temperatures were recorded 17.6-13.8.1992, 21.9.1995-15.8.1993, 12.9.1993-26.8.1994, 11.6-17.7.1995, 14.10.1995-8.6.1996, 10.6-17.7.1996 (Table 1). Intervals between individual recordings were 0.8 to 1.5 h during the growth seasons and 1.5 to 4.8 h during the winters, depending on the study year.

Table 1: Design of temperature records. Seasons: G, growth season (summer); A, autumn; W, winter; S, spring. Media monitored: a, air; s, soil.

	Years and seasons																
Site	1992				1993				1994				1995				1996
	G	A	W	S	G	A	W	S	G	A	W	S	G	A	W	S	G
15 N														s	s	s	
11 N														s	s	s	
3 N														s	s	s	
1 N													as	s	s	s	a
1 S	a													s	s	s	
5 S													as	s	s	s	a
7 S	a	a	a	a	a									s	s	s	
9 S													as	s	s	s	a
14 S	a	a	a	a	a	a	a	a	a				as	s	s	s	a
20 S														s	s	s	
29 S	a	a	a	a	a	a	a	a	a				as	s	s	s	a
47 S														s	s	s	
65 S													as	s	s	s	

2.3 Statistical analysis

Analysis was based on daily values, calculated from all records collected during 24 h period (field data: 16-30 records during growth seasons, 5-16 records between seasons; measurements at the meteorological station in Monchegorsk: 8 records). The data were divided into a training set (712 observations) used to build the model and a test set (77 observations made by 10, 20 and 30 day of each month) used to fit the model. Temperatures recorded at our study sites were regressed (with SAS REG procedure[34]) to records obtained in Monchegorsk, with the site-specific measures of pollution load (concentration of Ni) and topographic factors (altitude, distance to the nearest reservoir with the water surface >5 km^2) subsequently entering the linear model. To account for possible non-additive interactions, we tested also pairwise products of these measures as independent variables.

3 Results

3.1 Air temperatures

During the growth season, daily mean temperatures varied from -1 to +20°C. Site-specific daily means strongly correlated to each other (r=0.896-0.994, n=28-210 days, $P<0.0001$; mean R^2=0.93). Among-site correlations between daily maxima were slightly lower (r=0.832-0.953, $P<0.0001$; mean R^2=0.82) and correlations between daily minima were much lower (r=0.341-0.965, $P<0.05$; mean R^2=0.52) than correlations between daily means. The maximum difference in daily means (4.29°C) was recorded between sites situated in an industrial barren (1 km N from the smelter) and unpolluted forest (65 km SE). In industrial barrens, daily maxima were on an average 1°C higher and daily minima 2°C higher than in unpolluted forests; the difference in temperatures between these sites increased with a decrease in temperature.

Table 2: Site-specific regressions of daily mean air temperatures during the growth seasons to records of meteorological station in Monchegorsk.

Site	Years of observations	R^2_{adj}	Intercept		Slope	
			mean ± SE	P[a]	mean ± SE	P[b]
1 N	1995-1996	0.94	-0.94 ± 0.39	0.02	1.19 ± 0.04	<0.0001
1 S	1992	0.98	-0.02 ± 0.31	0.94	1.00 ± 0.03	0.33
5 S	1995-1996	0.94	-0.82 ± 0.38	0.04	1.15 ± 0.04	0.0002
7 S	1992-1993	0.97	-0.94 ± 0.20	<0.01	1.06 ± 0.02	<0.0001
9 S	1995-1996	0.90	-0.02 ± 0.49	0.97	1.11 ± 0.05	<0.0001
14 S	1992-1996	0.94	0.39 ± 0.18	0.03	1.06 ± 0.02	<0.0001
29 S	1992-1996	0.94	0.09 ± 0.16	0.60	0.96 ± 0.02	0.0058
65 S	1995	0.81	0.65 ± 0.92	0.48	0.97 ± 0.08	0.27

[a] Confidence limit for H0: mean=0, t-test (SAS REG procedure).
[b] Confidence limit for H0: mean=1, t-test (SAS UNIVARIATE procedure).

The site-specific daily mean temperatures correlated with data obtained from the meteorological station in Monchegorsk (Table 2). Both intercepts and slopes of site-specific regressions linearly correlated with foliar nickel concentrations (Fig. 1), hinting that mean temperature in a given site along the pollution gradient could be estimated from meteorological data obtained at another site combined with measurements of pollution load.

Stepwise regression based on a training set of observations resulted in a highly significant model ($F_{4,707}$=2730.2, $P<0.0001$, R^2_{adj}=0.94), with quite minor (1.3 %) but still highly significant contribution of among-site variation compared with the effect of daily temperature fluctuations (98.7 %). Altitude accounted for a half of the among-site variation, whereas another half depended mostly on the product of temperature and pollution load (Table 3). Distance to the nearest reservoir with the water surface >5 km², as well as other tested pairwise interactions between variables, did not enter the model at the significance level P=0.05.

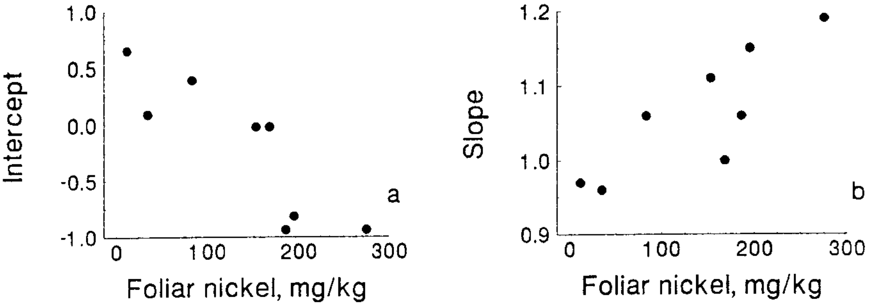

Figure 1: Correlation of slopes (a) and intercepts (b) from site-specific regressions of air temperatures to temperature records by meteorological station in Monchegorsk (Table 2) with pollution load (a, r=-0.87, P=0.005; b, r=0.84, P=0.009).

Table 3: Stepwise regression analysis of air temperatures in our study sites during the growth seasons. Variables: TM, records of meteorological station in Monchegorsk (°C); ALT, altitude of the study site (meters a.s.l.); NI, multi-year mean nickel concentration in birch foliage (mg kg^{-1}).

Variable	Partial R^2	Model R^2	Parameter Estimate	Standard Error	F	Prob>F
Intercept	-	-	2.13	0.25	70.6	0.0001
TM	0.9273	0.9273	0.960	0.018	2925.4	0.0001
ALT	0.0063	0.9335	-0.009283	0.001056	77.3	0.0001
TM*NI	0.0048	0.9384	0.000790	0.000137	33.2	0.0001
NI	0.0008	0.9392	-0.004454	0.001454	9.4	0.0023

3.2 Soil temperatures

In heavily polluted open habitats, soil freezing occurred 10-11 wks earlier and soil thawing 3-4 wks earlier than in unpolluted forests (Table 4). Dates (Julian days) of soil freezing and thawing correlated with site-specific pollution loads (r=-0.87, P<0.0001 and r=-0.71, P<0.01, respectively; n=13 sites). During the winter (1.12.1995-29.2.1996), mean soil temperature decreased with an increase in pollution (r=-0.68, n=13, P<0.01).

During the growth season, soil temperatures were highest in barrens. At sites with destroyed vegetation, soil temperatures fluctuated much following fluctuations in air temperatures, whereas in birch transitional communities and weakened spruce forests correlations between daily air and soil temperatures were low, and no correlation was found in unpolluted forest (Table 5).

Table 4: Soil temperature regime between growth seasons of 1995 and 1996.

Site	Date[a] of		Winter temperatures[b]		
	freezing	thawing	mean ± SE	min	max
15 N	18 Dec	2 Jun	-0.12 ± 0.01	-0.3	0.2
11 N	10 Nov	4 Jun	-0.73 ± 0.02	-1.5	-0.1
3 N	19 Oct	9 May	-8.77 ± 0.16	-19.9	-1.3
1 N	20 Oct	10 May	-3.75 ± 0.08	-7.5	-0.6
1 S	22 Oct	2 Jun	-0.52 ± 0.01	-1.0	-0.1
5 S	6 Nov	9 May	-1.10 ± 0.04	-3.0	-0.1
7 S	21 Oct	16 May	-6.77 ± 0.10	-12.2	-2.0
9 S	23 Nov	2 Jun	-1.57 ± 0.05	-3.3	-0.1
15 S	5 Jan	25 May	0.07 ± 0.02	-0.3	0.9
20 S	27 Dec	8 Jun	-0.02 ± 0.01	-0.3	0.4
29 S	7 Jan	3 Jun	0.12 ± 0.01	-0.1	0.7
47 S	31 Dec	19 May	0.12 ± 0.02	-0.1	0.7
65 S	24 Dec	7 Jun	-0.38 ± 0.02	-1.3	0.4

[a] The first day when daily mean temperature crossed 0°C.
[b] Based on daily means recorded from 1.12.1995 to 29.2.1996.

Table 5: Site-specific regressions of soil temperatures to air temperatures[a]

Site	R^2_{adj}	Intercept		Slope	
		mean ± SE	P[b]	mean ± SE	P[c]
1 N	0.52	6.87 ± 0.48	<0.0001	0.22 ± 0.04	<0.0001
5 S	0.35	7.23 ± 0.42	<0.0001	0.14 ± 0.03	<0.0001
9 S	0.63	6.85 ± 0.65	<0.0001	0.38 ± 0.05	<0.0001
14 S	0.08	8.35 ± 0.36	<0.0001	0.05 ± 0.03	0.05
29 S	0.08	8.01 ± 0.38	<0.0001	0.06 ± 0.03	0.06
65 S	0.00	6.67 ± 0.46	<0.0001	0.03 ± 0.04	0.52

[a] Based on daily means recorded from 11.6 to 17.7.1995.
[b] Confidence limit for H0: mean=0, t-test (SAS REG procedure).
[c] Confidence limit for H0: mean=1, t-test (SAS UNIVARIATE procedure).

4 Discussion

4.1 Sources of variation in air temperatures

The three most important topographic factors governing variation in temperature are latitude, altitude, and distance from the large bodies of water[10]. The relatively short extent of our study area from North to South (ca 60 km) allowed us to disregard effects of latitude. Slope in our plots was very minor and effects of slope exposure were therefore not accounted for. No effect of lakes was revealed by the stepwise regression analyses, but altitude of study sites, quite expectedly, had significant effect on temperature regime. Our model (Table 3) demonstrated a decrease of 0.93 ± 0.10°C with a 100 m increase in altitude which is reasonably close to the value of 0.6°C per 100 m, earlier reported for Tshuna and Khibiny Mts[37].

Pollution contributed to among-site variation in temperature regime mostly via an interaction between temperature and pollution load, whereas pollution alone explained only a few percent of this variation. Air temperatures in heavily polluted sites were lower in cool days (daily means below +5°C) but higher in warm days.

The long-term annual mean temperature in Monchegorsk is -0.5°C[3]. From our regression model (Table 3) we estimated that annual mean temperature in industrial barrens adjacent to the smelter is about 0.9°C lower than in unpolluted forests (-1.36°C and -0.50°C, respectively). If confounding effects of altitude are removed, the difference between heavily polluted and unpolluted habitats approaches 1.2°C. The latter value agrees with observations by Kryuchkov[22] who reported the 1 to 3°C decrease in annual temperature of industrial barrens compared with healthy forests.

4.2 Causal links between pollution load and microclimate

Aerial pollution may influence the heat balance of an area both directly and indirectly. Direct effects on temperature are caused by 9-15% increase in absorption of solar radiation[18, 23] which can reduce temperatures on the ground[41]. Furthermore, the nocturnal loss of the energy accumulated by aerosol particles increases the frequency of temperature inversions above the ground level and thus decreases heat loss during the nights[25]. Indirect effects are linked with pollution-induced changes in vegetation which may influence both absorption and loss of solar energy, and therefore affect the structure of the boundary layer, local wind circulation and the precipitation regime[9].

Our study sites represent different stages of pollution-related decline of coniferous forests[19]. Forest microclimate differs in many details from that of open habitats[10, 26, 35], and forest effects on temperature regime depend primarily on closeness and transparency of canopies[13]. At early stages of forest decline pollution may affect temperatures primarily by an increase in canopy transparency[30], which appear in coniferous forests due to decrease in needle life span, decrease in needle density per unit of shoot length, suppression of shoot elongation and death of the uppermost twigs in the crown[22, 42]. Death of damaged trees in the absence of regrowth also increases soil exposure to solar radiation in weakened forests. Thinning of the canopies, in agreement with earlier studies[10, 16, 30], resulted also in an increase in both mean summer soil temperature and daily temperature fluctuations along our pollution gradient.

Within the area of complete forest damage, a positive correlation between summer temperature and pollution load is presumably caused by an increase of soil exposure due to a decline of the ground vegetation cover (which has twice the albedo of barren soils[14]) from 70-90 % at the external border of transitional communities to 1-3 % in industrial barrens[19]. This situation resembles in some details changes in the energy balance observed in alpine plant communities, where leaf area decreased and amounts of attached dead plant parts increased with an increase in altitude[8]. Soil moisture in barrens is lower than in forests (pers. obs.), which also contributes to faster heating of soils and decreases transpiration-related heat loss. Similar mechanisms (low albedo and low transpiration) are responsible for temperature increase in large cities[25].

Another similarity in temperature regime between cities and industrial barrens concerns extremal temperatures. Both maximum and minimum temperatures in cities[25] and barrens were higher than in surrounding forests, which contrasted open grassland habitats where maximum temperatures are higher but minimum temperatures are lower than in adjacent forests[10, 35]. To our opinion, both the increased frequency of temperature inversions in polluted habitats[25] and the decreased transpiration may decrease nocturnal heat loss in cities and barrens compared with undisturbed grasslands.

A layer of snow falling on unfrozen ground may prevent freezing during protracted periods of low temperatures[11]. The large (up to 11 weeks!) difference in the date of soil freezing between industrial barrens and healthy forests indicates that barren soils void of vegetation and exposed to lower air temperatures (see above) were already frozen by the time of appearance of snow cower. Furthermore, higher wind speeds in open habitats contributed to snow accumulation in low places, whereas in other microhabitats the snow layer is thinner than in forests. Enhanced wind induced compaction of snow particles in areas of industrial barrens may also lead to higher mean snow densities, as observed in the mountain tundra[37]. A thin and compact snow layer does not prevent further decrease of soil temperatures in industrial barrens during the winter time (Table 4). The absence of shade in treeless habitats and a large amount of dust particles in snow of heavily polluted areas (ca 3 times higher than in reference site[24]) may contribute to enhanced absorption of solar radiation and may thus lead to early soil thawing.

4.3 Biological effects of pollution-induced changes in microclimate

Microclimatic changes recorded in polluted habitats may (1) directly affect seasonal development and performance of plants and animals, (2) lead to combined effects including the pollution-induced damage by (i) pollution-induced changes in sensitivity to extremal temperatures or (ii) temperature-related changes in sensitivity to pollutants.

The interaction between pollution load and temperature discovered in the course of the present study explains some discrepancies in phenological observations conducted along pollution gradients. Some phenological events, like budbreak of Scots pine (*Pinus sylvestris*)[42] and mountain birch (pers. obs.), occur in industrial barrens later than in forests, whereas flowering of rowan-tree (*Sorbus aucuparia*) and willow-weed (*Chamenerion angustifolium*) as well as appearance of several mid-summer moth species are first recorded in barrens (pers. obs.). This results from faster accumulation of thermal sums in industrial barrens than in unpolluted forests: in early spring, barrens are cooler than forest, but in mid-summer they became warmer. The overall balance of thermal budget is profitable for barrens: they accumulated ca 10% more degree-days during the growth season. Thus, heat-loving plants and ectothermic animals developing in mid-summer, including the majority of herbivorous insects, may benefit in heavily polluted habitats from an increase in temperature. An increase in mean temperature by 1 °C increases plant productivity by ca 10%[15]; for mountain birch, the corresponding increase in leaf biomass approaches 20% (pers. obs.). This beneficial effect may alleviate or even compensate growth decrease resulting from pollutant toxicity[17, 40].

Alterations in soil temperatures were found to increase rootlet mortality in yellow birch, together with mycorrhizal dieback[31]. Furthermore, increased soil temperatures during the growth season may decrease root hardening[33] which, in combination with pollution-induced decrease in cold-hardiness[38], increases the probability of death from freezing injury in severely polluted habitats, which are more cold in winter time than healthy forests. Similar effects of pollution were also suggested for some ectothermic animals[43]. And inversely, temperature may affect the sensitivity to pollution in both plants[27, 28, 29] and animals[43]. Thus, observed forest decline in polluted habitats, although presumably triggered by pollution, could not be attributed to toxic effects of pollutants alone: initial pollution-induced forest disturbance, through secondary effects, may enhance further disturbance in a positive feedback fashion[30].

To conclude, pollution-related modifications of the microclimate may increase, mask or compensate toxic effects of emissions and should therefore be accounted for in field studies conducted along pollution gradients.

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