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Sigurður H. Magnússon and Björn Thomas

Unnið fyrir Alcan á Íslandi

NÁTTÚRUFRÆÐISTOFNUN ÍSLANDS

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Styrkur þungmálma og brennisteins í mosa í nágrenni álversins í Straumsvík árið 2005

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ABSTRACT

As a part of the UN-ECE International Cooperative Programme on vegetation and air borne pollution, moss samples of *Hylocomium splendens* were taken all over Iceland in 2005 and analysed for heavy metals (As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, V, Zn) and sulphur (S). Additionally, the areas around the aluminium smelter in Straumsvík, ferro-silicon plant and aluminium smelter at Grundartangi, west Iceland and aluminium smelter at Reyðarfjörður, east Iceland were sampled more intensively. This report uses the data of the 2005 and the previous 2000 study for monitoring airborne depositions in these areas and to separate different emission sources.

In general, all measured elements were found in higher concentration in the vicinity of the Straumsvík smelter than in the background area. Two main emission sources could be identified, the aluminium smelter itself and a nearby industrial area. Arsenic (As), nickel (Ni) and sulphur (S) are clearly emitted by the aluminium smelter, whereas chromium (Cr), Copper (Cu), Iron (Fe), lead (Pb), vanadium (V) and zinc (Zn) are mainly originating from the industrial area located 1.0-1.5 km to the southeast of the smelter. Statistical analyses reveal a decrease in concentration of some elements (Cr, Cu, Ni, Pb and S) close to the smelter between 2000 and 2005 which indicates a reduction in pollution.

Lykilorð
heavy metals, deposition patterns, mosses, industrial sites, aluminium smelter, Iceland

Yfirfarið
BM, PH, SB

ÁGRIP

Sumarið 2005 fór fram á Náttúrufræðistofnun Íslands rannsókn á þungmálmum og brennisteini í mosa á Íslandi í samvinnu við Umhverfisstofnun og fleiri aðila. Rannsóknin er liður í fjölþjóðlegu vöktunarverkefni þar sem meginmarkmið er að fylgjast með mengun sem berst með lofti og að finna helstu uppsprettur hennar. Í þessum tilgangi hefur tildurmosa (*Hylocomium splendens*) verið safnað víðs vegar um land á 5 ára fresti allt frá árinu 1990 og þungmálmar greindir. Árið 2000 var mosa einnig safnað til mælinga á þungmálmum bæði við álverið í Straumsvík og í nágrenni fyrirhugaðs álvers í Reyðarfirði. Var það hugsað sem upphaf vöktunar á þungmálmum við álverin. Sumarið 2005 voru þessar rannsóknir endurteknar og vöktun einnig hafin í nágrenni verksmiðjanna á Grundartanga.

Við rannsóknirnar árið 2005 voru tekin 11 mosasýni á fjórum sniðum við álverið í Straumsvík og styrkur As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, V, Zn og S ákvarðaður með ICP-tækni. Við úrvinnslu voru notaðar niðurstöður úr þeim sýnum sem safnað var á landinu öllu árin 2000 og 2005. Styrkur þungmálma og brennisteins var kannaður eftir fjarlægð frá álverinu (<3 km, 3–100 km og >100 km) og einnig borinn saman við styrk efna við fyrirhugðað álver í Reyðarfirði (<3 km) og við iðjuverin á Grundartanga (<3 km).

Styrkur flestra þeirra efna sem mæld voru í rannsókninni reyndist vera hærri í nágrenni álversins í Straumsvík en bakgrunnsgildin gefa til kynna. Þessi áhrif eru þó mjög mismikil eftir efnum. Einna mest eru þau á blý (Pb), nikkel (Ni), arsen (As) og sink (Zn) en minnst á vanadíum (V) og járn (Fe).

Útbreiðslumynstur efnanna við álverið í Straumsvík er aðallega tvenns konar sem gefur til kynna mismunandi uppruna. Annars vegar eru efni sem greinilega koma frá álverinu en styrkur þeirra er hæstur við álverið en minnkar síðan í allar áttir með fjarlægð. Þetta eru efnin arsen (As), nikkel (Ni) og brennisteinn (S). Hinsvegar eru efni sem koma að öllum líkindum frá iðnaði og annarri starfsemi sem staðsett er austan við álverið. Þar er um að ræða blý (Pb), sink (Zn), kopar (Cu), króm (Cr), járn (Fe) og vanadíum (V). Útbreiðsla kadmíums (Cd) og kvikasilfurs (Hg) gefur hinsvegar til kynna að þau eigi að nokkru leyti uppruna á báðum þessum stöðum.

Af þeim efnum sem frá álverinu koma er styrkur arsens (As) og þó einkum nikkels (Ni) allhár við álverið hvort sem litið er til norðurevrópskra eða íslenskra bakgrunnsgilda og eru hæstu gildin í Straumsvík u.þ.b. fimmföld á við styrk efnanna á Reykjanesskaga. Brennisteinn, sem álverið losar í allmiklu magni, mælist einnig nokkru hærri við álverið en á Reykjanesskaga en hæstu gildin í Straumsvík eru þó ekki þau hæstu á landinu (3. viðauki).

Í nágrenni álversins hafa orðið nokkrar breytingar á styrk efna milli 2000 og 2005. Styrkur nikkels (Ni) og brennisteins (S) minnkaði og svipað á við um styrk blýs (Pb), kopars (Cu) og króms (Cr). Ekkert efnanna jókst hinsvegar marktækt í nágrenni álversins í Straumsvík á þessum tíma sem bendir til þess að nokkuð hafi dregið úr mengun þungmálma og brennisteins.

Á stórum svæðum á landinu urðu einnig töluverðar breytingar á styrk efna sem ekki verða raktar til innlends iðnaðar eða beint til umsvifa manna hér á landi. Styrkur nikkels (Ni), járns (Fe) og vanadíums (V) jókst t.d. sem að öllum líkindum má rekja til aukins áfoks. Styrkur kvikasilfurs (Hg), sinks (Zn), blýs (Pb) og brennisteins (S) minnkaði, sennilega vegna minnkandi mengunar erlendis frá.

Niðurstöður rannsóknanna við Straumsvík sýna að þar er allmikil staðbundin mengun, einkum 1,0–1,5 km suðaustur af álverinu. Miðað við magn einstakra efna og líklegan uppruna þeirra má ætla að mengun af völdum álversins sé þar nokkur en hún er sennilega enn meiri frá öðrum iðnaði í nágrenninu.

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1 INTRODUCTION

In Europe, carpet-forming mosses have been widely used since the late 1960's for assessing regional and temporal variability of atmospheric heavy-metal deposition (Rühling and Tyler 1969). In Iceland, concentration of heavy metals has been systematically monitored since 1990, at a five year interval, as a part of the UN-ECE International Cooperative Programme on vegetation (Rühling et al. 1992, Rühling and Steinnes 1998, Buse et al. 2003).

The moss technique for monitoring of heavy metal depositions has several advantages (see e.g. Rühling and Steinnes 1998, Buse et al. 2003). Mosses lack a cuticle and transport tissue and therefore absorb whatever is in the air or water around them. In addition particles are adsorbed onto their surface. This results in accumulation of heavy metals in the moss both from dry and wet deposition (Rühling and Steinnes 1998). As moss sampling is relatively simple and the concentration of heavy metals is generally much higher in the moss than in the air, analysis of the moss tissue is both a cheap and easy way to identify pollution in the environment.

As in any indirect method, there are factors other than pollution that influence the concentration of heavy metals in mosses (Berg et al. 1995, Steinnes 1995, Reimann et al. 2001). Input from marine environment is known to affect the metal concentration. Metals can be transported from the soil to roots of plants and subsequently reach the mosses from the living or dead plant tissue. In moist or wet areas, especially following snowmelt, contact between the soil and water can transport metals from the soil to the mosses. Furthermore windblown dust from soil can affect the metal content.

The results of the 1990 and 1995 moss surveys in Iceland indicated an increased concentration of some heavy metals in the vicinity of the aluminium smelter in Straumsvík (Rühling et al. 1992, Rühling and Steinnes 1998). In the 2000 survey, additional samples were taken around the Straumsvík smelter but also around the proposed aluminium smelter in Reyðarfjörður. This was done to get a clearer spatial picture of the heavy metal concentration around the smelters but also to act as first step in monitoring the discharge of heavy metals from them (Magnússon 2002a and 2002b). In the 2000 survey 11 elements were analyzed, 10 heavy metals (As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, V, Zn) and sulphur (S). In the 2005 survey sampling at these sites was repeated. The industrial site at Grundartangi, western Iceland, was also added to the study.

The aluminium smelter in Straumsvík produces about 480 tons of aluminium each day and has an annual capacity of 178.000 tons (Alcan Iceland 2007). East of and adjacent to the aluminium smelter there is an industrial area that has been expanding in recent years. It consists among others of metal processing companies and an asphalt plant (Figure 1).

This report focuses on the heavy metal and sulphur concentration in mosses around the aluminium smelter in Straumsvík and compares the findings with the areas in Grundartangi and Reyðarfjörður. The aim is to display and explain the spatial distribution of heavy metal concentrations around the aluminium smelter. In the discussion, background values from Iceland and Europe are considered. This, and the previous study, is part of an ongoing monitoring of the impacts of the aluminium smelter. Previous studies on aluminium smelters in Norway (Steinnes et al. 2001, Magnússon 2002a) help to identify impacts of the smelter in Straumsvík and to separate them from confounding effects of the industrial area.

2 METHODS

In the vicinity of the aluminium smelter in Straumsvík, the moss *Hylocomium splendens* was sampled at 11 sample points located along four transects (I–IV) on October 12th, 2005. All samples were collected at the same locations as in the preceding study of 2000 (Magnússon 2002a) (Figur 1). The first transect leads from the western coastline of Straumsvík west parallel to the main road from Reykjavík to Keflavík. The second starts by a small pond southwest of the smelter and heads southwest. The third heads southeast and the fourth covers the area east of the smelter toward the town of Hafnarfjöður. At each transect three samples were taken about 1100, 1700 and 2500 m from the centre of the smelter. However, at transect IV only two samples were collected, due to limited area between the smelter and the town Hafnarfjörður. There the samples were taken at relatively undisturbed surfaces located between golf fields in that area. In the 2000 survey, the main characteristic of the sample points were described (Magnússon 2002a). In the sampling of 2005 these characteristics have been revised and additionally photos taken in order to give an overview of the present conditions (Table 1).

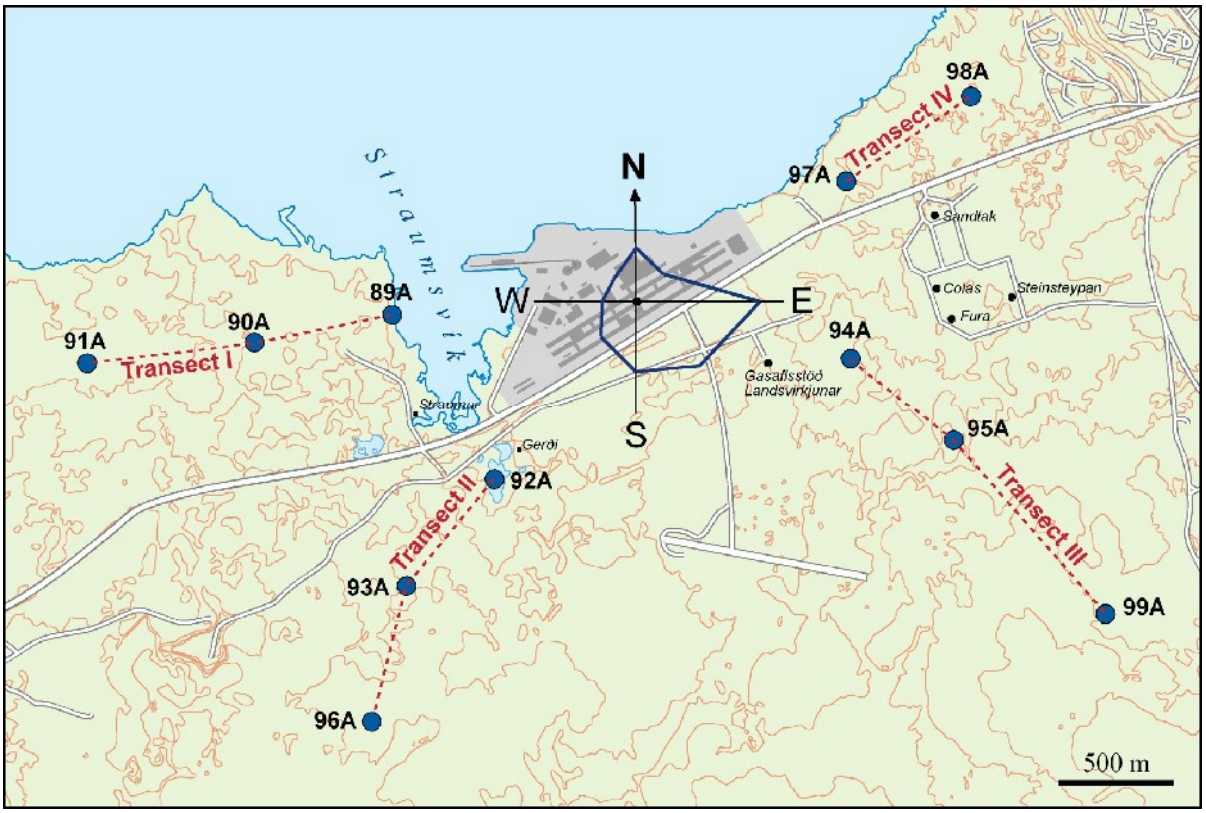


Figure 1. The aluminium smelter site in Straumsvík and adjacent area. Locations of transects and points where moss samples were collected in 2005 for determination of heavy metals are marked (blue dots). The location of other main industrial activities in the area (see also Appendix 1) and the relative frequency of wind directions from January 2002 to December 2004 is also shown. - Álverið í Straumsvík og nágrenni þess. Sýnatökustaðir mosa árið 2005 eru númeraðir og táknaðir með bláum punktum. Sýnd er tíðni vindátta frá janúar 2002 til desember 2004. Staðsetning nokkurra iðnfyrirtækja austan við álverið er einnig sýnd.

Table 1. *Location and characteristics of the sampling points near the aluminium smelter in Straumsvík (revised from Magnússon 2002a).* - Staðsetning og helstu einkenni sýnatökustaða við álverið í Straumsvík. Endurskoðaðar upplýsingar frá Sigurði H. Magnússyni (2002).

Tran-sect *Snið*	No. *Númer*	Distance to smelter, m *Fjarlægð frá álveri, m*	m asl *Hæð yfir sjó, m*	Slope [°]/ direction *Halli [°]/ Hallastefna*	Vegetation/land type *Gróður-land/gerð*	Dominant vascular plants	Ríkjandi háplöntutegundir
I	89A	1100 m	5	4/NE	Grassland on lava *Graslendi á hrauni*	*Agrostis capillaris* *Anthoxanthum odoratum* *Festuca vivipara* *Galium boreale*	Hálíngresi Ilmreyr Blávingull Krossmaðra
I	90A	1700 m	10	1/E	Grassy heath on lava *Graslendi á hrauni*	*Agrostis capillaris* *Festuca vivipara* *Trisetum spicatum* *Anthoxanthum odoratum*	Hálíngresi Blávingull Lógresi Ilmreyr
I	91A	2400 m	10	2/E	Heathland *Mólendi*	*Empetrum nigrum* *Festuca richardsonii* *Festuca vivipara* *Trisetum spicatum*	Krækilyng Túnvingull Blávingull Lógresi
II	92A	1000 m	10	4/N	Grassy heath on lava *Graslendi á hrauni*	*Agrostis capillaris* *Festuca vivipara* *Galium boreale* *Galium verum*	Hálíngresi Blávingull Krossmaðra Gulmaðra
II	93A	1600 m	20	4/N	Grassy heath on lava *Graslendi á hrauni*	*Agrostis capillaris* *Empetrum nigrum* *Festuca vivipara* *Deschampsia flexuosa*	Hálíngresi Krækilyng Blávingull Bugðupuntur
II	96A	2200 m	20	1/NE	Heathland on lava *Mólendi á hrauni*	*Empetrum nigrum* *Calluna vulgaris* *Deschampsia flexuosa* *Agrostis capillaris*	Krækilyng Beitilyng Bugðupuntur Hálíngresi
III	94A	1000 m	20	1/W	Heathland on lava *Mólendi á hrauni*	*Empetrum nigrum* *Calluna vulgaris* *Arctostaphylos uva-ursi* *Deschampsia flexuosa*	Krækilyng Beitilyng Sortulyng Bugðupuntur
III	95A	1500 m	20	0	Heathland on lava *Mólendi á hrauni*	*Calluna vulgaris* *Empetrum nigrum* *Arctostaphylos uva-ursi* *Betula pubescens*	Beitilyng Krækilyng Sortulyng Birki
III	99A	2500 m	40	0	Heathland on lava *Mólendi á hrauni*	*Calluna vulgaris* *Betula pubescens* *Empetrum nigrum* *Arctostaphylos uva-ursi*	Beitilyng Birki Krækilyng Sortulyng
IV	97A	1100 m	10	1/NW	Grassy heath on lava *Graslendi á hrauni*	*Empetrum nigrum* *Calluna vulgaris* *Festuca vivipara* *Deschampsia flexuosa*	Krækilyng Beitilyng Blávingull Bugðupuntur
IV	98A	1800 m	10	2/SE	Grassy heath on lava *Graslendi á hrauni*	*Agrostis capillaris* *Galium boreale* *Empetrum nigrum* *Kobresia myosuroides*	Hálíngresi Krossmaðra Krækilyng Þursaskegg

The sampling was conducted according to the monitoring manual of the European heavy metal deposition monitoring program (Harmens 2005). At every sampling point, 5-10 sub-samples of the moss *Hylocomium splendens* were taken within a 50 m by 50 m plot and placed together in a plastic bag. Moss growing under other plants was not sampled to avoid subsequent metal transport from the soil to the moss. At sample point 94A, the moss was very sparse and only found growing in depressions. There the sampling area was enlarged to obtain enough moss for analysis.

After sampling, the moss samples were kept frozen until February 2006. They were then thawed and cleaned of dead material and attached litter. Segments from the 2005 growing season were separated and discarded and only the growth segments of 2002, 2003 and 2004 kept for analysis. The separated material was then put into paper bags and dried at room temperature. The samples were sent to the Section of Plant Ecology and Systematics of the University of Lund, Sweden, for analysis. Before analysis the samples were dried at 40 °C and wet ashed with nitric acid. From each sample, 1 g of moss was used for the analysis. Cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), nickel (Ni), lead (Pb), vanadium (V) and zinc (Zn) were measured with inductively coupled plasma emission spectrometry (ICP-ES) and arsenic (As), mercury (Hg) and sulphur (S) with inductively coupled plasma mass spectrometry (ICP-MS) technique. The quantification limits are listed in Appendix 2. The remaining part of each moss sample was dried at room temperature and kept for possible future investigations.

3 DATA ANALYSES

For the analyses, the data from the 2000 and 2005 surveys were used. Each data set was divided into three classes according to the distance from the Straumsvík smelter; < 3 km, 3–100 km, > 100 km. In addition, sampling points within 3 km of the industries at Grundartangi (aluminium smelter and ferro-silicon plant) and the aluminium smelter site in Reyðarfjörður were grouped respectively and used for comparison to the Straumsvík data. The mean for each distance class was calculated together with standard error (SE) and presented in graphs. Comparison of the elements between sites and distance classes were made with one-way ANOVA on log transformed values for each survey respectively. Comparison of site means was then made with the Tukey-Kramer HSD test (JMP 2005).

Comparison between years (2000 vs. 2005) was done on paired samples with a paired t-test on log transformed values for each site or distance class separately; Straumsvík < 3 km (n=11), 3–100 km (n=23), > 100 km (n=75), Reyðarfjörður < 3 km (n=4). The sampling points close to Grundartangi (< 3 km) were excluded from this test due to few samples (n=2).

The results are also presented with maps showing the metal concentration at each sampling point, thus giving an overview of the spatial distribution of heavy metal concentrations near the Straumsvík smelter. In accordance with the European moss sampling program (Buse et al. 2003) the legend of the maps is adapted to the colours generally used in their presentation of overall results. This ensures a more objective view on the data, as only highest values in the European context are highlighted in red or orange. In addition the samples from the Icelandic surveys of 2000 and 2005 are ranked in order to make their relative comparison more easy (Appendix 3).

4 RESULTS AND DISCUSSION

The samples represent the deposition from 2002 to 2004. During this period, wind directions between east and south were most frequent in the area (Figure 1).

4.1 Arsenic (As)

The arsenic concentration in 2005 was highest near to the smelter and decreased along the transects (Figure 2). The highest concentrations were found in the two samples located about 1 km southeast and west of the smelter.

By comparing sites and distance classes, the arsenic concentration in 2005 was found to be significantly higher close to the aluminium smelter in Straumsvík (> 3 km) than in any other class except close to the industries at Grundartangi (> 3 km) (Figure 2). In Straumsvík the measured values are among the highest in Iceland (Appendix 3). The results of the previous study in 2000 showed a similar pattern except that the concentration of arsenic close to the industries at Grundartangi was at that time significantly lower than in Straumsvík. On the Reykjanes peninsula which can be considered as a background area for Straumsvík the values differed between 0.16 and 0.24 µg/g.

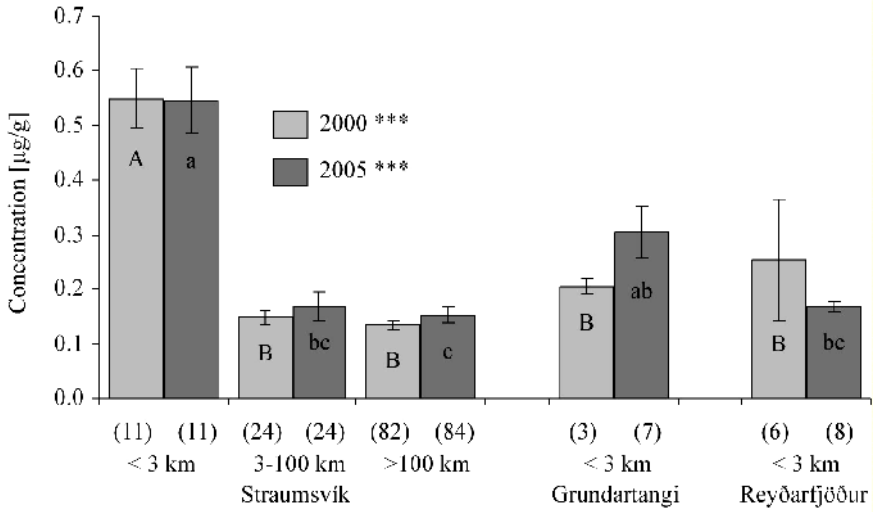
Comparison of paired samples for the different distance classes and sites did not reveal any significant difference between years.

The distribution of arsenic in moss in Straumsvík, with the highest values close to the smelter, strongly indicates that the element is emitted by the aluminium smelter. These findings are in line with earlier results both from Straumsvík and from several Norwegian smelters (Steinnes et al. 2001, Magnússon 2002a). However, as sample 94A had highest concentration of arsenic it is not possible to exclude additional impacts by other industries in the area (Figure 2).

Compared to European values, the highest arsenic concentration in Straumsvík is similar to that found close to industrialised areas but considerably higher than most of the background values in Scandinavia (< 0.2 µg/g) (Rühling and Steinnes 1998, Buse et al. 2003).

Arsenic (As)

A.



B.

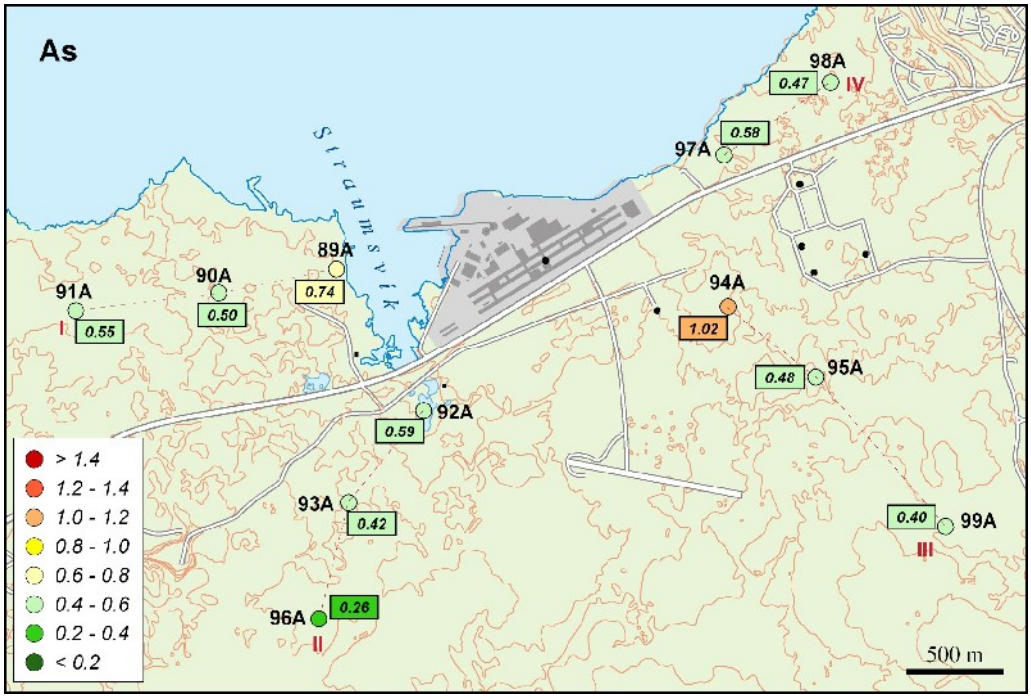


*Figure 2. (A) Average arsenic (As) concentration at different distances (<3 km, 3-100 km, >100 km) from the aluminium smelter in Straumsvík for the 2000 and 2005 moss survey. For comparison the average arsenic concentration close (<3 km) to the ferro-silicon plant and aluminium smelter at Grundartangi and aluminium smelter site in Reyðarfjörður is given. Standard error is shown with vertical lines and the number of samples is displayed in parentheses below. Stars attached to the years denote significance between classes tested with ANOVA (NS: not significant, *: p <0.05, **: p<0.01, ***: p<0.001). Different letters in the columns denote significant difference between distance classes and sites, capital letters for the year 2000 and small for 2005 (p<0.05, Tukey test).* - Styrkur arsens (As) í mosa í mismunandi fjarlægð frá álverinu í Straumsvík (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur arsens í nágrenni iðnaðarsvæðanna á Grundartanga og í Reyðarfirði. Lóðréttar línur tákna staðalskekkju. Innan sviga er sýndur fjöldi sýna í hverjum flokki. Stjörnur við ártöl sýna marktækan mun á svæðum og stöðum metið með fervikagreiningu (NS: ekki marktækt, *:p <0,05, **: p<0,01, ***:p<0,001). Mismunandi bókstafir tákna marktækan mun milli svæða, stórir stafir fyrir árið 2000 en litlir fyrir árið 2005, metið með Tukey prófun (p<0,05).

(B) Spatial distribution of arsenic concentration in mosses along the sampling transects <3 km to the aluminium smelter in Straumsvík in 2005. The colour scale reflects the European range of arsenic (Buse et al. 2003). - Styrkur arsens í mosa í Straumsvík og nágrenni. Litakvarði er miðaður við skýrslu Buse o.fl. frá árinu 2003.

4.2 Cadmium (Cd)

The cadmium concentration found in the 2005 survey around the aluminium smelter in Straumsvík varied from 0.06 to 0.19 µg/g. The highest concentrations were found in the area southeast of the smelter and they were about twice as high as other values within the 3 km zone (Figure 3). Compared to other samples in Iceland, the values close (>3 km) to the Straumsvík smelter are comparatively high (Appendix 3).

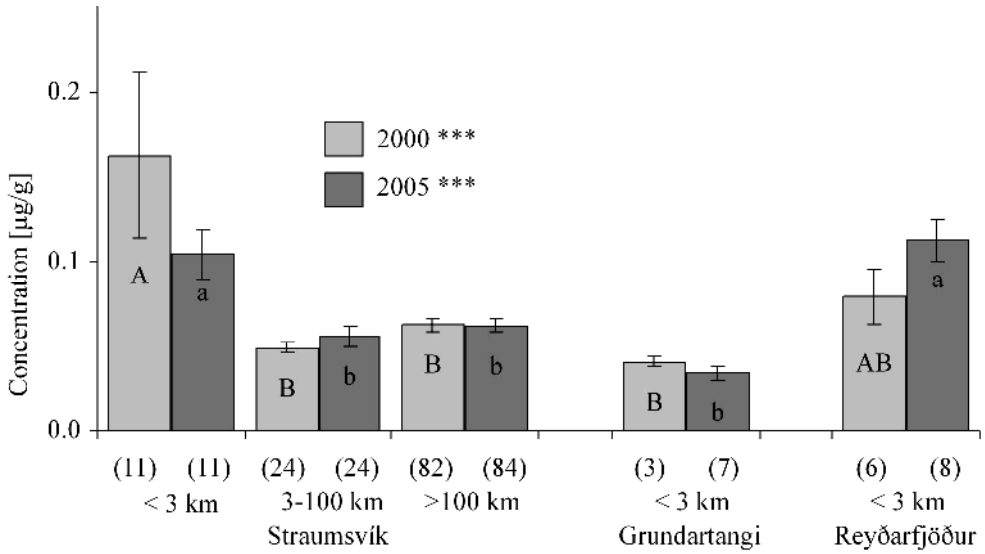
Data analysis shows significant differences in cadmium concentration between the distance zone close to the Straumsvík smelter (> 3 km) and the others, except Reyðarfjörður (<3 km) for 2000 and 2005 (Figure 3). However, the paired test could not find significant differences between the two sampling years for any distance class or site.

The present results show a small increase in cadmium concentration close to the smelter which indicates that the smelter is an emission source. However, the smelter is not necessarily the only source in the area. Higher values along the third transect indicate that other industries in the area are likely to emit cadmium (Figure 3).

Results from Norway denote a similar pattern. There concentration of cadmium is generally higher near aluminium smelters than in background areas (Steinnes et al. 2001, Magnússon 2002a). Compared to the European data, the values in Straumsvík are not remarkably higher than the background concentration e.g. in Norway or Sweden but they are much lower than in the most areas of Central Europe (Rühling and Steinnes 1998, Buse et al. 2003).

Cadmium (Cd)

A.



B.

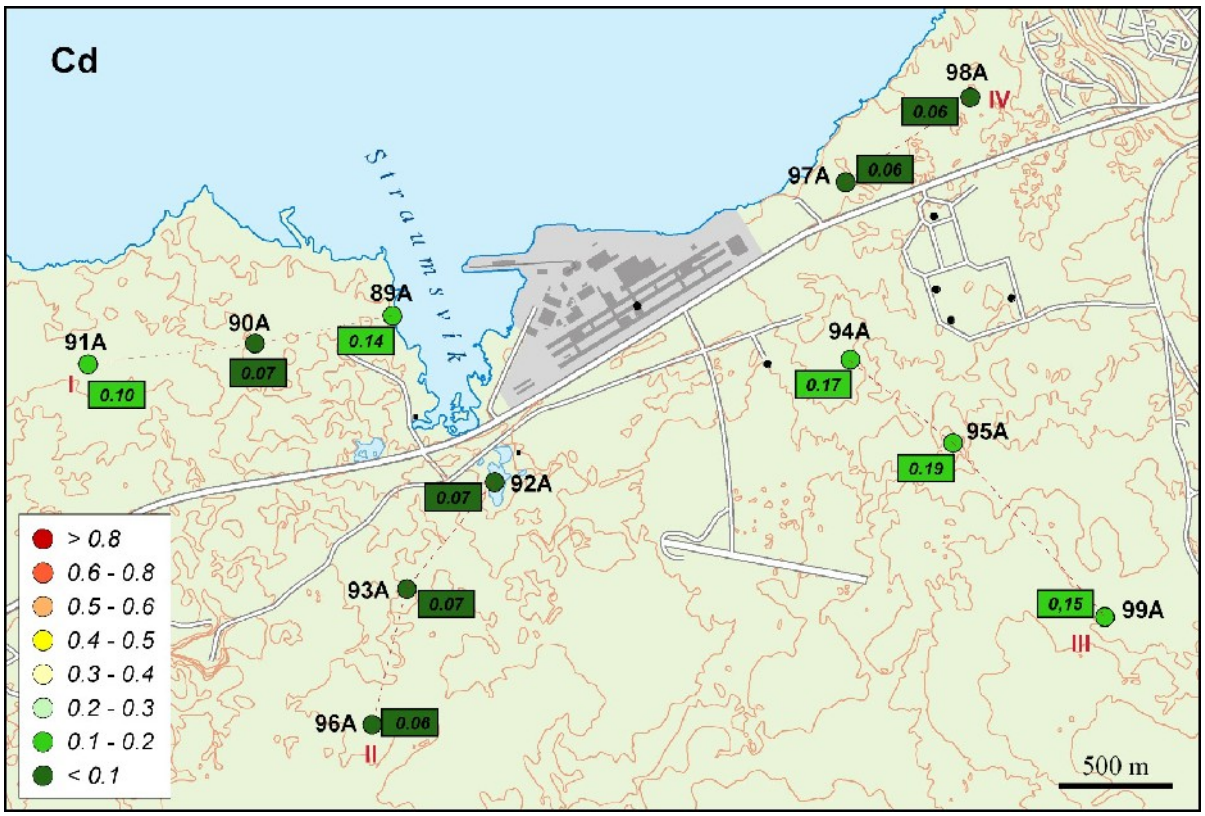


Figure 3. (A) Average cadmium (Cd) concentration at different distances (<3 km, 3-100 km, >100 km) from the aluminium smelter in Straumsvík for the 2000 and 2005 survey and at the industrial sites at Grundartangi and in Reyðarfjörður. - Styrkur kadmíums (Cd) í mosa í mismunandi fjarlægð frá álverinu í Straumsvík (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur kadmíums í nágrenni iðjuveranna á Grundartanga og í Reyðarfirði.

(B) Spatial distribution of cadmium concentration in mosses along the sampling transects <3 km to the aluminium smelter in Straumsvík in 2005. The colour scale reflects the European range of cadmium (Buse et al. 2003). For details see also Figure 2. - Styrkur kadmíums í mosa í Straumsvík og nágrenni. Litakvarði er miðaður við skýrslu Buse o.fl. frá árinu 2003. Nánari skýringar eru á 2. mynd.

4.3 Chromium (Cr)

The results from the 2005 survey show that chromium concentrations close to the smelter in Straumsvík differ greatly and range from 1.95 to 9.38 µg/g. Transect III and IV show about two to four times higher values than transect I and II, with the highest values in an area 1000–1500 m northeast to southeast of the smelter (Figure 4). Compared to other samples in Iceland the highest values in Straumsvík (>3 km) are among the 20 highest samples in the country (Appendix 3).

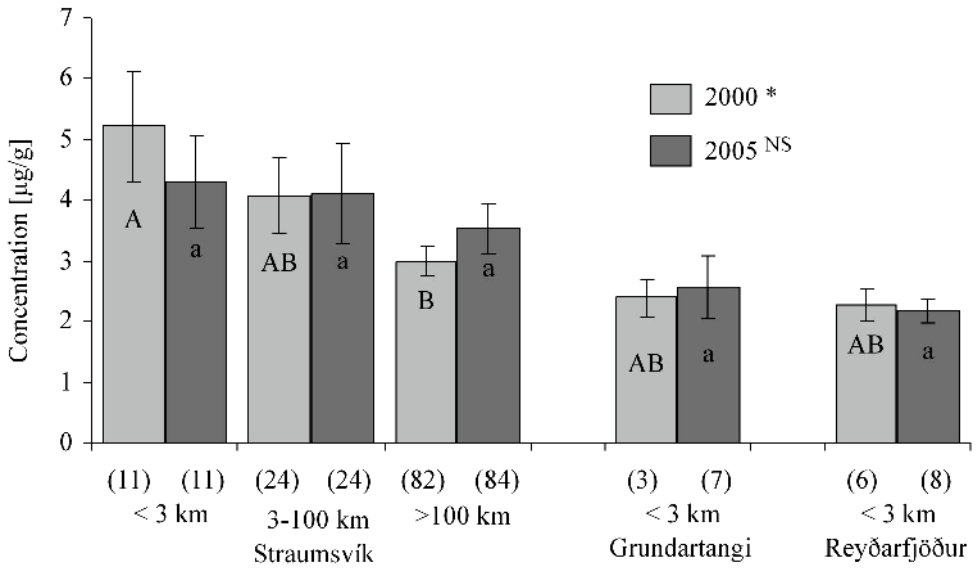
The results also show that in 2005, the values close to the smelter (<3 km) did not differ significantly from other distance classes (3–100 km, >100 km) or sites compared (Figure 4). In the 2000 survey, similar results were obtained except that the concentration close to Straumsvík smelter was significantly higher than values in the > 100 km distance zone (Figure 4). Furthermore, comparison of paired values for different times and distance zones revealed no significant differences except for the samples close to Straumsvík (<3 km). There the concentration had decreased on average from 5.21 to 4.30 µg/g from 2000 to 2005 ($P < 0.01$, $n=11$).

In Iceland, relative high concentrations of chromium are probably due to high airborne dust in areas of active soil erosion, especially within the volcanic active zone (Rühling and Steinnes 1998). These effects are not that distinctive on the Reykjanes peninsula. Transect I and II, and especially sample 89A and 92A close to the smelter, show low chromium concentrations. Thus the aluminium smelter seems to have little increase effect on the other two transects. Higher amounts of dust from the industries in the area and emission from the nearby metal grating and processing industry probably have the biggest effect on samples from those two transects.

Compared to the European range, the highest values close to Straumsvík in 2005 are higher than the background values in Scandinavia but similar to many industrialized areas of Central Europe (Rühling and Steinnes 1998, Buse et al. 2003).

Chromium (Cr)

A.



B.

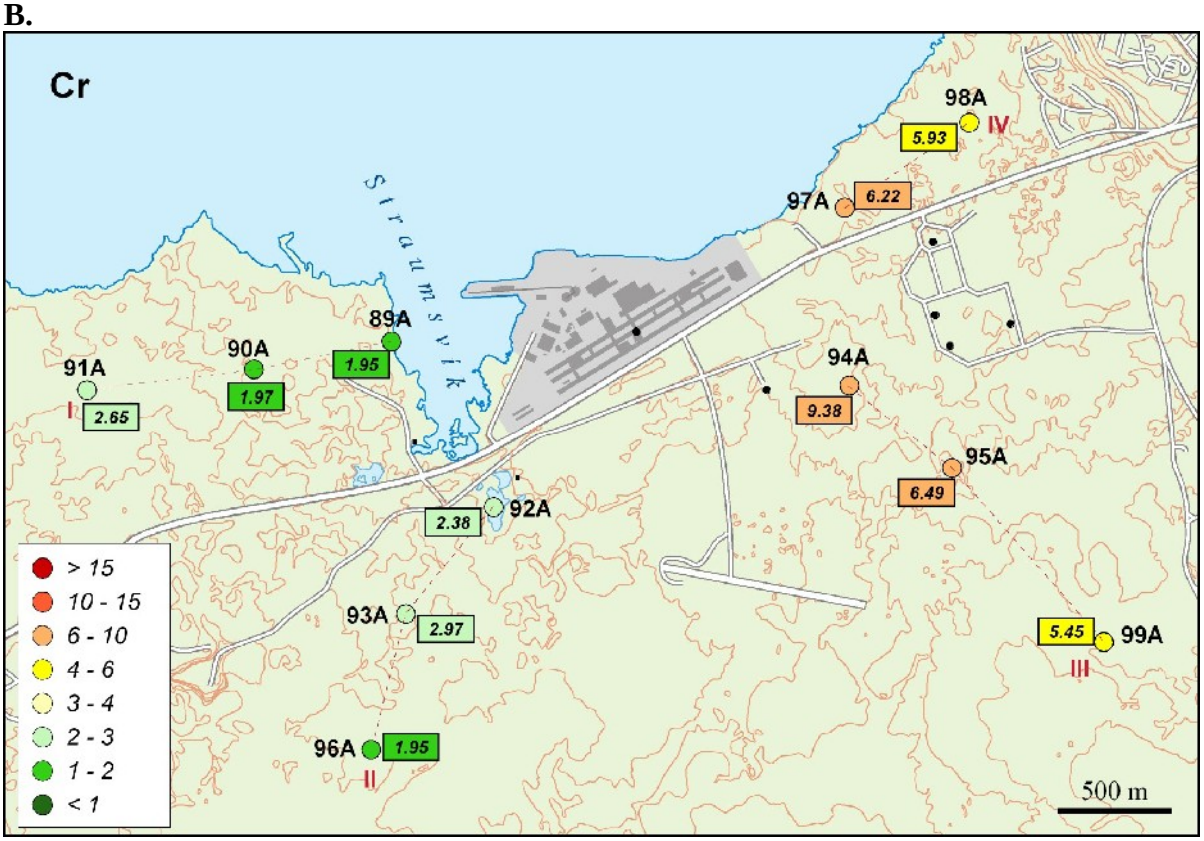


Figure 4. (A) Average chromium (Cr) concentration at different distances (<3 km, 3-100 km, >100 km) from the aluminium smelter in Straumsvík for the 2000 and 2005 survey and at the industrial sites at Grundartangi and in Reyðarfjörður. - Styrkur króms (Cr) í mosa í mismunandi fjarlægð frá álverinu í Straumsvík (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur króms í nágrenni iðjuveranna á Grundartanga og í Reyðarfirði.

(B) Spatial distribution of chromium concentration in mosses along the sampling transects <3 km to the aluminium smelter in Straumsvík in 2005. The colour scale reflects the European range of chromium (Buse et al. 2003). For details see also Figure 2. - Styrkur króms í mosa í Straumsvík og nágrenni. Litakvarði er miðaður við skýrslu Buse o.fl. frá árinu 2003. Nánari skýringar eru á 2. mynd.

4.4 Copper (Cu)

In the 2005 survey, copper concentration ranged from 5.30 to 25.38 µg/g in the area close to the Straumsvík smelter (<3 km) (Figure 5). The lowest values were found west and southwest of the smelter (transects I and II) but the highest east of the smelter (transects III and IV) with a maximum at sample 94A. Compared to other samples in Iceland the highest values in Straumsvík are among the 20 highest in the country (Appendix 3).

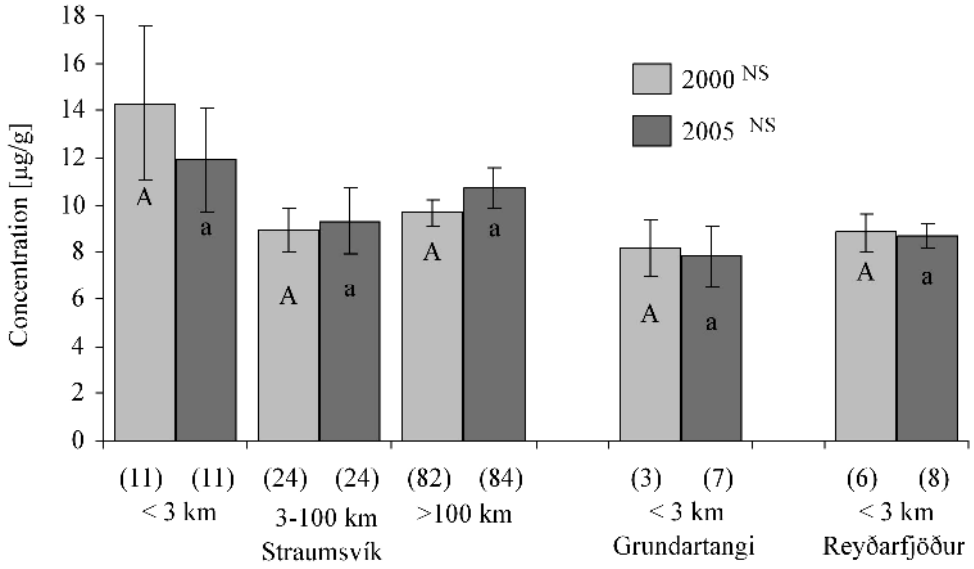
Although not significant, the values around the smelter (<3 km) were on average higher than within other distance classes (3-100 km, >100 km) and at the other two sites Grundartangi and Reyðarfjörður (Figure 5). Comparison of paired values did not reveal significant difference between the years of survey except for the Straumsvík site. There the copper concentration had decreased significantly from 14.3 to 11.9 µg/g during these five years ($P < 0.05$, $n=11$).

Results from aluminium smelters in Norway have shown that concentration of copper is somewhat higher close to the factories than the background levels (Steinnes et al. 2001, Magnússon 2002a). According to those results aluminium smelters may be a source of copper. However, the distribution pattern of copper concentration in the present study in Straumsvík strongly indicates that the main source of copper is rather related to the industries operating to the east of the smelter. Similar pattern was also found in the 2000 survey (Magnússon 2002a).

The copper values from Straumsvík and for Iceland as a whole are, in a European context, relatively high which is partly related to volcanism and erosion in the country (Rühling and Steinnes 1998, Buse et al. 2003).

Copper (Cu)

A.



B.

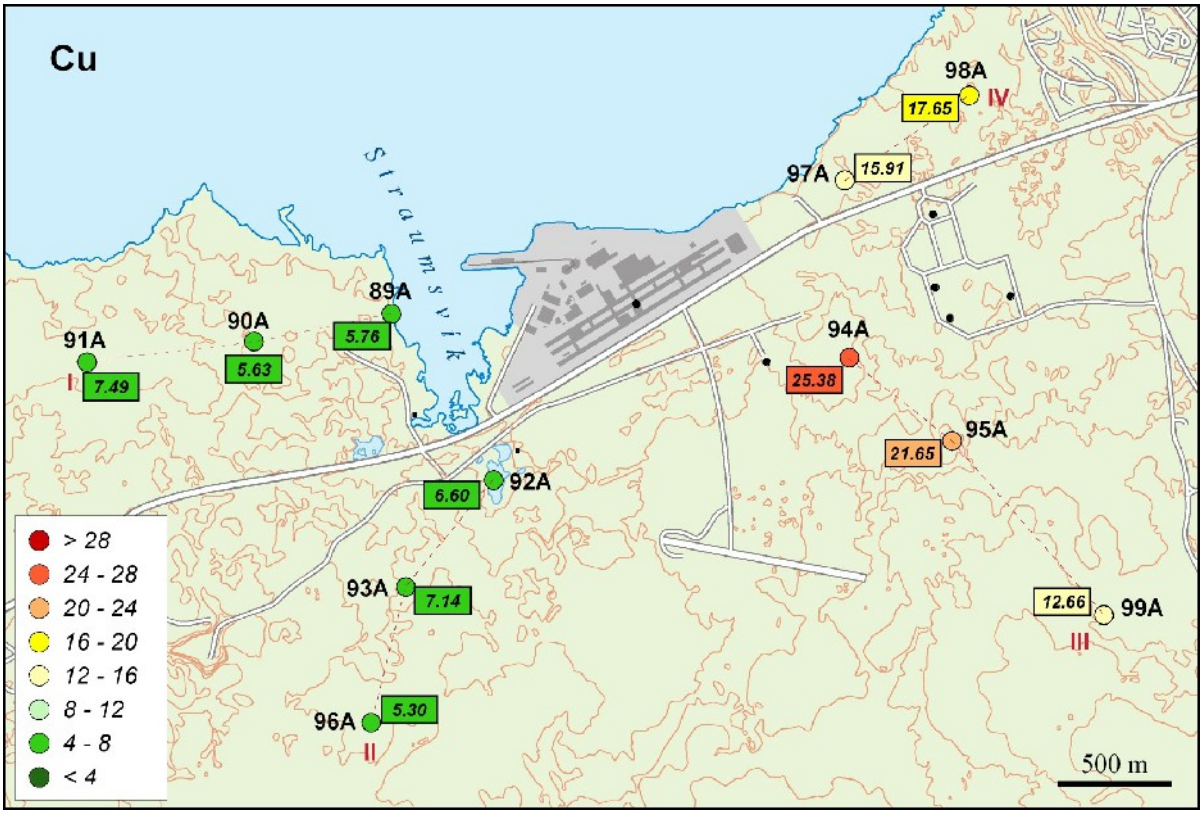


Figure 5. (A) Average copper (Cu) concentration at different distances (<3 km, 3-100 km, >100 km) from the aluminium smelter in Straumsvík for the 2000 and 2005 survey and at the industrial sites at Grundartangi and in Reyðarfjörður. - Styrkur kopars (Cu) í mosa í mismunandi fjarlægð frá álverinu í Straumsvík (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur kopars í nágrenni iðjuveranna á Grundartanga og í Reyðarfirði.

(B) Spatial distribution of copper concentration in mosses along the sampling transects <3 km to the aluminium smelter in Straumsvík in 2005. The colour scale reflects the European range of copper (Buse et al. 2003). For details see also Figure 2. - Styrkur kopars í mosa í Straumsvík og nágrenni. Litakvarði er miðaður við skýrslu Buse o.fl. frá árinu 2003. Nánari skýringar eru á 2. mynd.

4.5 Iron (Fe)

In the 2005 survey, iron concentration in mosses around the aluminium smelter in Straumsvík varied greatly and showed a clear pattern of distribution. The area east of the smelter had about twice as high concentration (transects III and IV, 5233–7035 µg/g) as the area to the west of the smelter (transects I and II, 2848–4342 µg/g) (Figure 6). The highest value (7035 µg/g) was found at sample 94A located about 1 km southeast of the smelter but also close to the other industries in the area. However, the highest iron concentration values in Straumsvík were only intermediate or slightly above average compared to the country as a whole (Appendix 3).

Comparison of iron concentration between distance classes or sites did not reveal any significant difference for either the 2005 or the 2000 survey (Figure 6). However, comparison of paired values showed an increase in the concentration from 2000 to 2005 for samples at distance > 100 km (5598 to 6650 µg/g, $P < 0.05$, $n=74$).

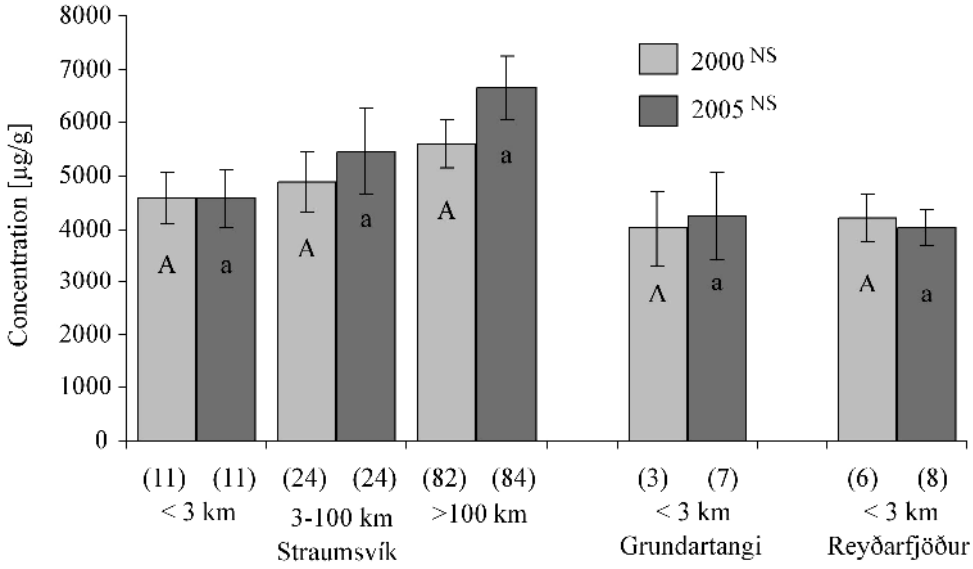
In Iceland, the highest concentrations of iron are found within the volcanic active zone and are related to soil dust and volcanic ash (Rühling et al. 1992). On the Reykjanes peninsula, the values fall mostly between 3000 to 5000 µg/g. These values can be seen as background concentration for the Straumsvík area.

Thus the aluminium smelter appears to have non significant impact on the iron concentration in the samples. Instead the results strongly indicate that the industrial area southwest of the smelter is a source for the high iron concentrations measured in the moss samples from transects III and IV.

Comparison of the present results and European studies (Rühling and Steinnes 1998, Buse et al. 2003) is meaningless due to the high background concentration in Iceland.

Iron (Fe)

A.



B.

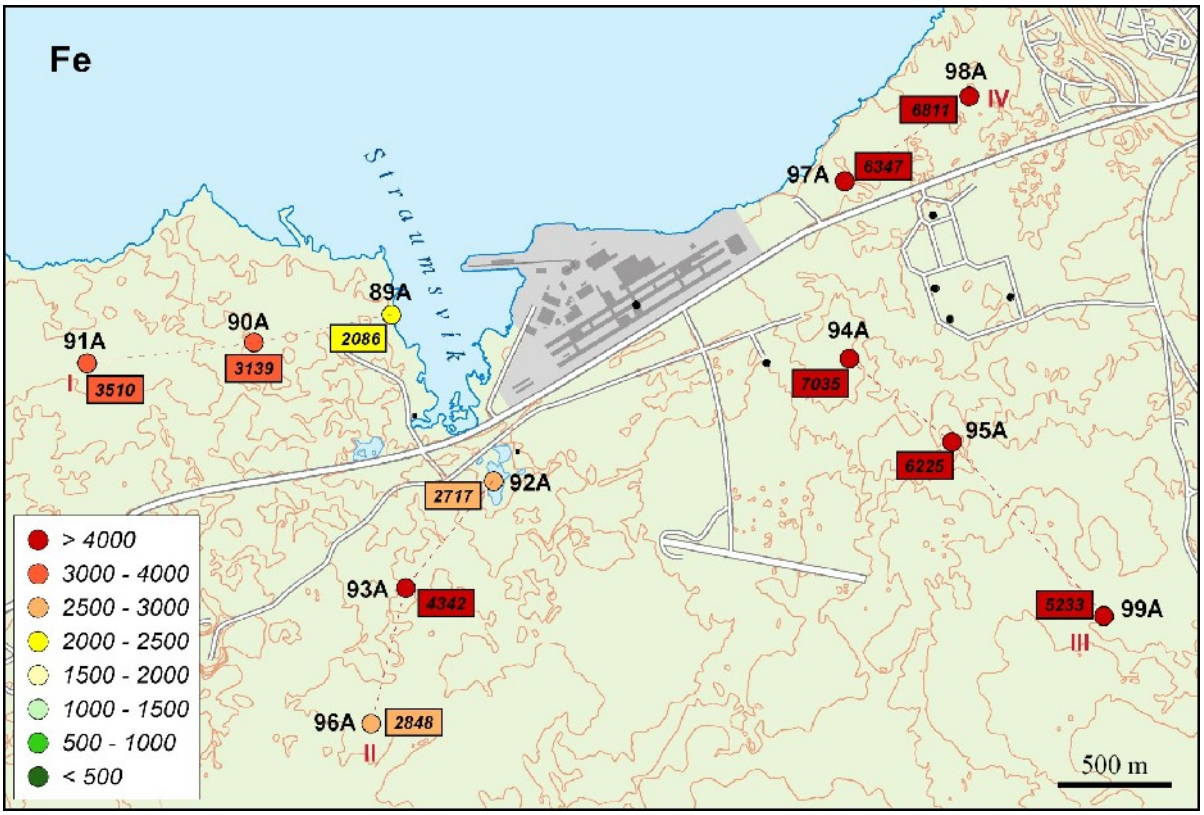


Figure 6. (A) Average iron (Fe) concentration at different distances (<3 km, 3-100 km, >100 km) from the aluminium smelter in Straumsvík for the 2000 and 2005 survey and at the industrial sites at Grundartangi and in Reyðarfjörður. - Styrkur járns (Fe) í mosa í mismunandi fjarlægð frá álverinu í Straumsvík (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur kadmíums í nágrenni iðjuveranna á Grundartanga og í Reyðarfirði.

(B) Spatial distribution of iron concentration in mosses along the sampling transects <3 km to the aluminium smelter in Straumsvík in 2005. The colour scale reflects the European range of iron (Buse et al. 2003). For details see also Figure 2. - Styrkur járns í mosa í Straumsvík og nágrenni. Litakvarði er miðaður við skýrslu Buse o.fl. frá árinu 2003. Nánari skýringar eru á 2. mynd.

4.6 Mercury (Hg)

In the 2005 survey, mercury concentration in Straumsvík (< 3 km) ranged from 0.009 to 0.059 µg/g (Figure 7). The concentration pattern indicates a weak increase effect in the area around the smelter, especially on the eastern side. The highest value, which is also the highest in Iceland (Appendix 3), was measured in sample 94A about 1 km southeast of the factory.

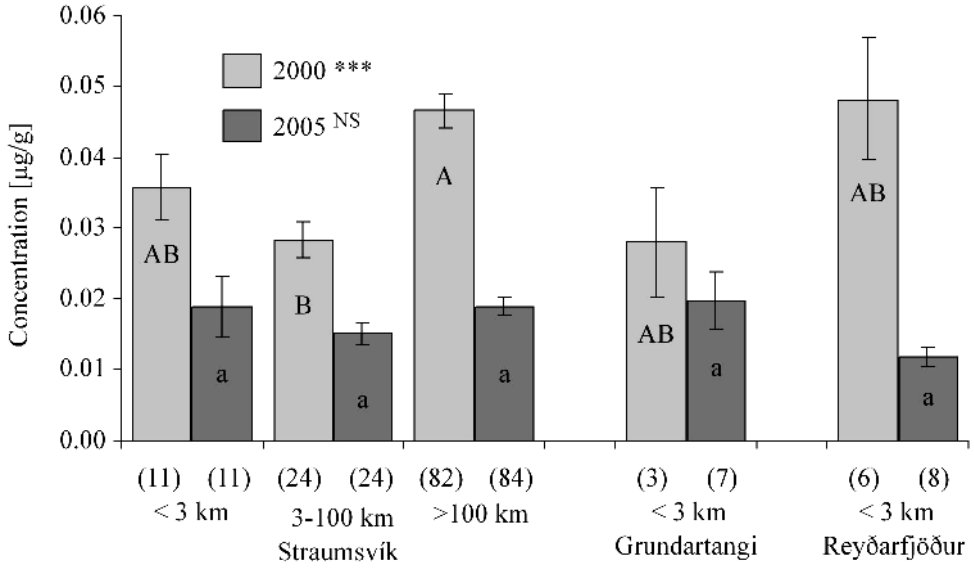
On average, the concentration of mercury in the survey of 2005 was quite constant over the distance classes and sites investigated and no significant difference was found among them (Figure 7). However, in the 2000 survey, a significant difference was observed between two distance classes (3-100 km and > 100 km) (Figure 7). The test of paired values showed that mercury had decreased significantly between years for all distance classes and sites compared. Between the surveys of 2000 and 2005 the mercury concentration decreased as follows: Straumsvík <3 km distance class, from 0.036 to 0.019 µg/g ($P < 0.001$, n=11), 3-100 km distance class, from 0.028 to 0.015 µg/g ($P < 0.001$, n=22), >100 km distance class, from 0.046 to 0.019 ($P < 0.001$, n=74, Reyðarfjörður from 0.048 to 0.012 µg/g ($P < 0.01$, n=4).

Results from earlier moss analyses in Norway and also from the Straumsvík area indicate that aluminium smelters have no or very little influence on mercury deposition (Steinnes et al. 2001, Magnússon 2002a). However, recent results from Grundartangi suggest a small impact by the local industries on mercury concentration (Magnússon and Thomas 2007). In general the values around the smelter in Straumsvík are low as in Scandinavia or remote areas of Europe (Rühling and Steinnes 1998, Buse et al. 2003).

Mercury is one of the metals which is readily transported over long distances (Poikolainen et al. 2004). In Iceland no strong local emission sources for mercury are known. Therefore, the observed decrease in concentration found in the 2005 survey may be explained by decrease of long-range transport of mercury to Iceland (Working Group on Effects 2004).

Mercury (Hg)

A.



B.

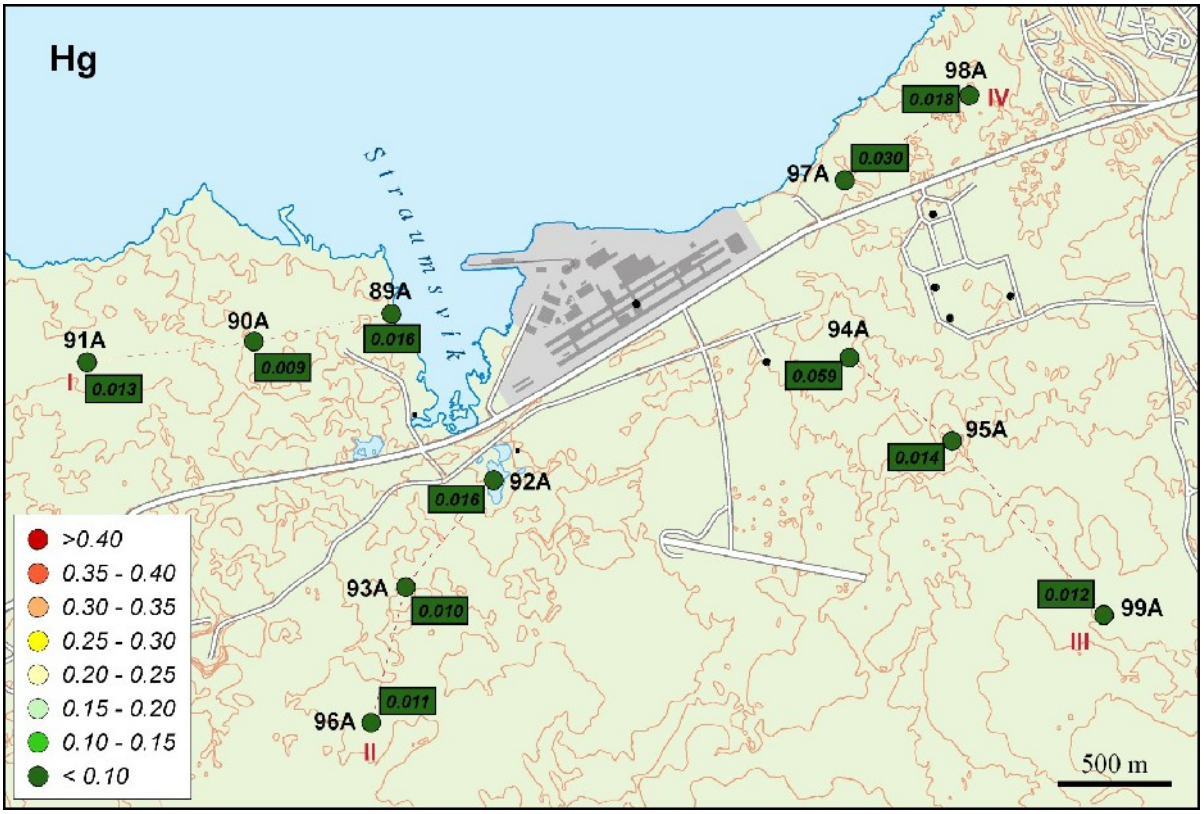


Figure 7. (A) Average mercury (Cd) concentration at different distances (<3 km, 3-100 km, >100 km) from the aluminium smelter in Straumsvík for the 2000 and 2005 survey and at the industrial sites at Grundartangi and in Reyðarfjörður. - Styrkur kvikasilfurs (Cd) í mosa í mismunandi fjarlægð frá álverinu í Straumsvík (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur kvikasilfurs í nágrenni iðjuveranna á Grundartanga og í Reyðarfirði.

(B) Spatial distribution of mercury concentration in mosses along the sampling transects <3 km to the aluminium smelter in Straumsvík in 2005. The colour scale reflects the European range of mercury (Buse et al. 2003). For details see also Figure 2. - Styrkur kvikasilfurs í mosa í Straumsvík og nágrenni. Litakvarði er miðaður við skýrslu Buse o.fl. frá árinu 2003. Nánari skýringar eru á 2. mynd.

4.7 Nickel (Ni)

The results from the 2005 survey show that the nickel concentrations around the aluminium smelter in Straumsvík are relatively high at all transects and decrease with distance to the smelter. The samples closest to the factory have concentrations of up to 33.6 µg/g (94A) and the concentration decreases to 9.0 µg/g at the end of Transect II (Figure 8). All the values from the Straumsvík site are among the highest encountered in the country (Appendix 3).

These high values of the 2005 survey are also reflected in the statistical results which show that concentration of nickel close to the smelter (<3 km) is significantly higher than within any other distance class or site (Figure 8). Similar pattern was also observed for the 2000 survey but then the > 100 km class was even significantly lower in nickel than the 3-100 km distance class. Additionally, comparison of paired values show a decrease in nickel concentration between the 2000 and 2005 survey for samples closer than 3 km to the smelter (from 21.6 to 18.8 µg/g, $P < 0.05$) but an increase for the distance classes 3-100 km (from 5.1 to 6.6 µg/g, $P < 0.001$, n=22) and > 100 km (from 3.3 to 5.1 µg/g, $P < 0.001$, n=74).

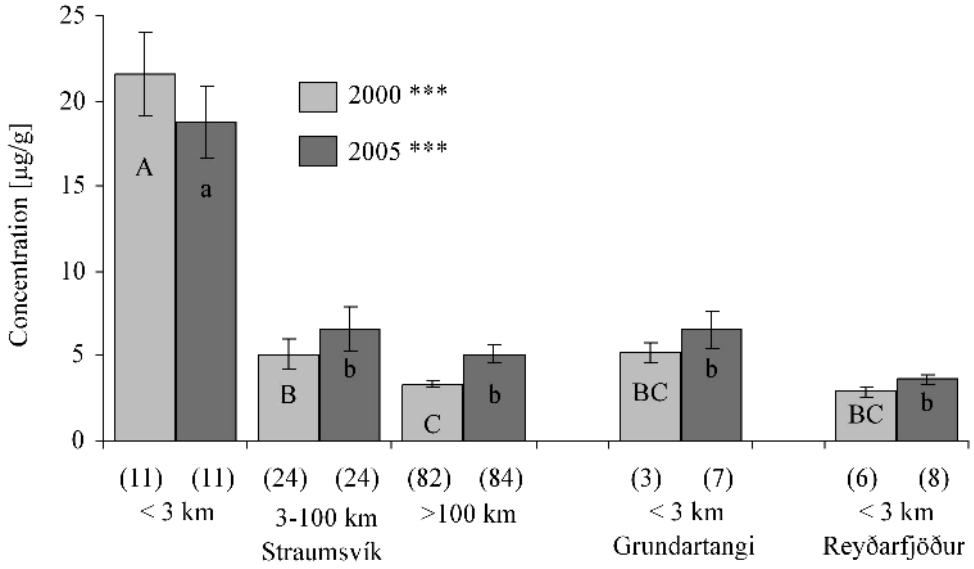
These high values of nickel close to the smelter in Straumsvík are in accordance with earlier results from Norway and new results from Grundartangi, Iceland which show that nickel concentration in mosses close to aluminium smelters is higher than in their background areas (Steinnes et al. 2001, Magnússon 2002a, Magnússon and Thomas 2007).

Therefore, the concentration pattern in Straumsvík strongly indicates that the smelter is the main source of nickel deposition in the area. However, additional influences from other industries can not be excluded.

Compared to European values, the concentrations around Straumsvík are very high and similar to other smelter regions e.g. in north Scandinavia (Rühling and Steinnes 1998, Buse et al. 2003). Although Iceland has a higher background concentration than other northern European countries, the concentrations in Straumsvík exceed by far the background range.

Nickel (Ni)

A.



B.

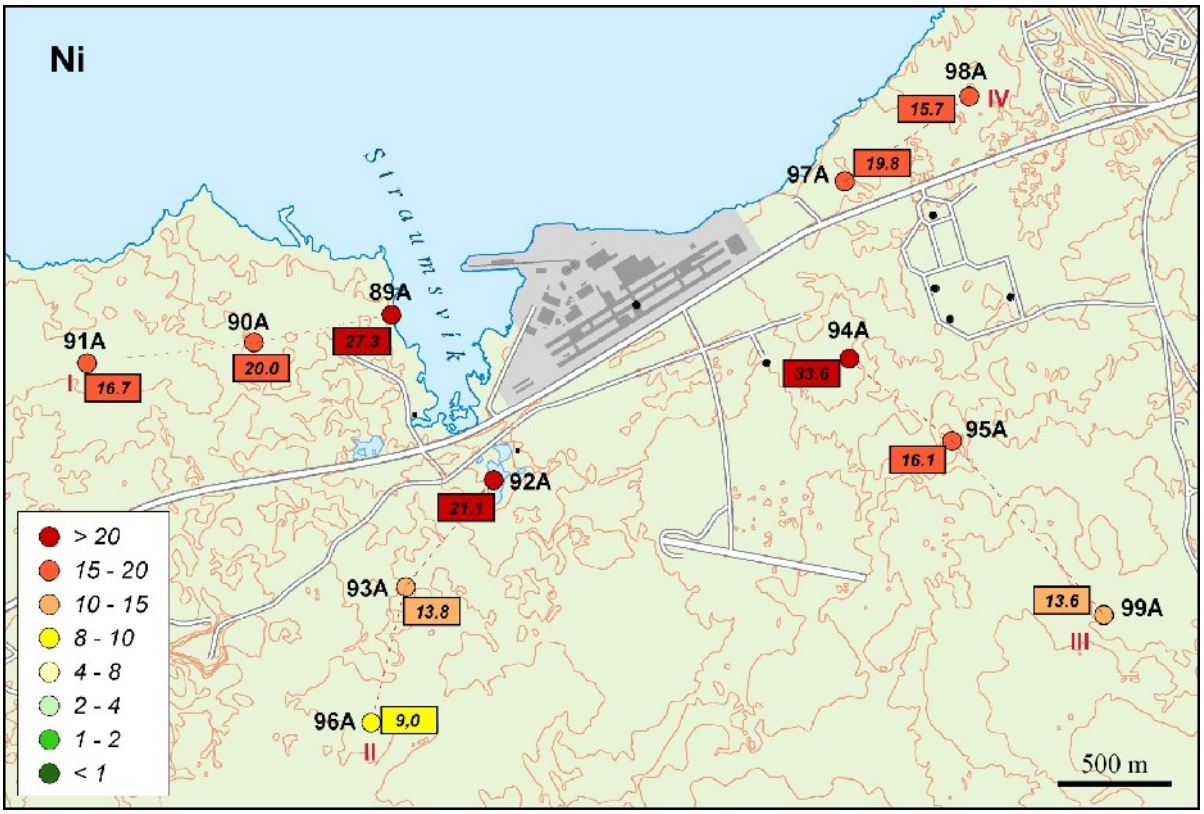


Figure 8. (A) Average nickel (Ni) concentration at different distances (<3 km, 3-100 km, >100 km) from the aluminium smelter in Straumsvík for the 2000 and 2005 survey and at the industrial sites at Grundartangi and in Reyðarfjörður. - Styrkur nikkels (Ni) í mosa í mismunandi fjarlægð frá álverinu í Straumsvík (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur nikkels í nágrenni iðjuveranna á Grundartanga og í Reyðarfirði.

(B) Spatial distribution of nickel concentration in mosses along the sampling transects <3 km to the aluminium smelter in Straumsvík in 2005. The colour scale reflects the European range of nickel (Buse et al. 2003). For details see also Figure 2. - Styrkur nikkels í mosa í Straumsvík og nágrenni. Litakvarði er miðaður við skýrslu Buse o.fl. frá árinu 2003. Nánari skýringar eru á 2. mynd.

4.8 Lead (Pb)

Results from the 2005 survey shows that concentration of lead in mosses around the aluminium smelter in Straumsvík ranges from 1.86 to 36.95 µg/g (Figure 9). The highest values were found in samples 94A and 95A on transect III, about 1 km southeast of the smelter and close to the industrial site. From that site the concentration is in general decreasing in all directions. Compared to the other samples in the country the highest values in Straumsvík also had the highest rank of all samples in Iceland in 2005 (Appendix 3).

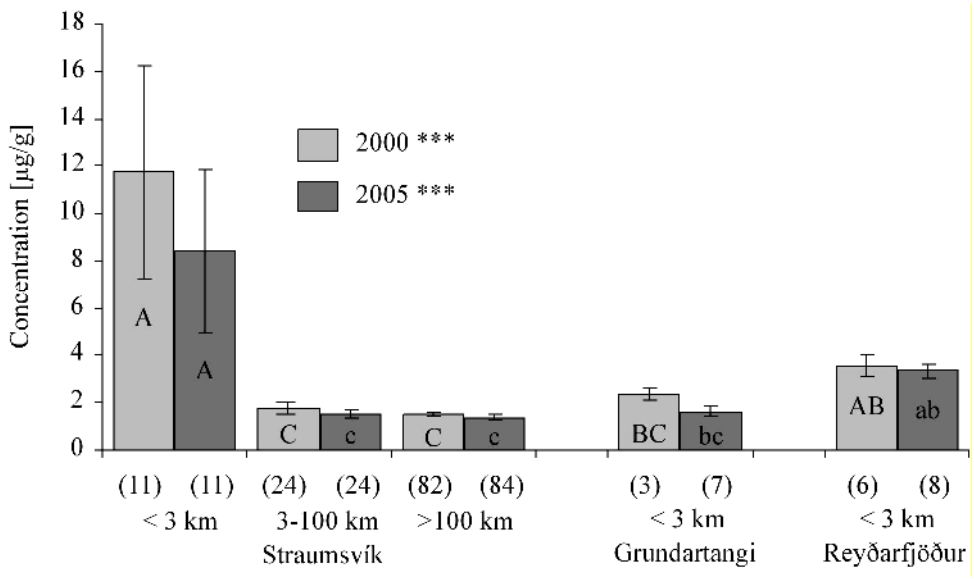
Comparisons of distance classes and sites gave similar statistical results for 2000 and 2005. In both years the values close to the smelter were significantly higher than other groupings compared except the Reyðarfjörður site in the 2000 survey. (Figure 9). Comparison of paired values showed that lead had decreased between years at all sites and areas compared, although not significantly for Reyðarfjörður. The results were as following for the year 2000 and 2005 respectively: Distance class < 3 km, 11.74 to 8.39 µg/g ($P < 0.001$, n=11); 3-100 km, 1.79and 1.50 µg/g, ($P < 0.05$, n=22); > 100 km, 1.51 and 1.37 µg/g ($P < 0.01$, n=74); Reyðarfjörður, 4.46 and 3.15 µg/g ($P=0.85$, n=4).

As transect I and II in Straumsvík showed very low concentrations and similar to the background in Iceland, the smelter seems to have no significant influence on the lead concentration in the mosses in the area. The source of relatively high deposition at transect III is very likely related to the other industrial activity southeast of the smelter. Similarly, investigations from Norway and from Grundartangi show that aluminium smelters do not affect the lead concentration of nearby growing mosses (Steinnes et al. 2001, Magnússon 2002a, Magnússon and Thomas 2007).

The relatively high values at transect III and IV are striking as they are similar or higher than the highest values found in earlier moss surveys in northern Europe (Rühling and Steinnes 1998, Buse et al. 2003).

Lead (Pb)

A.



B.

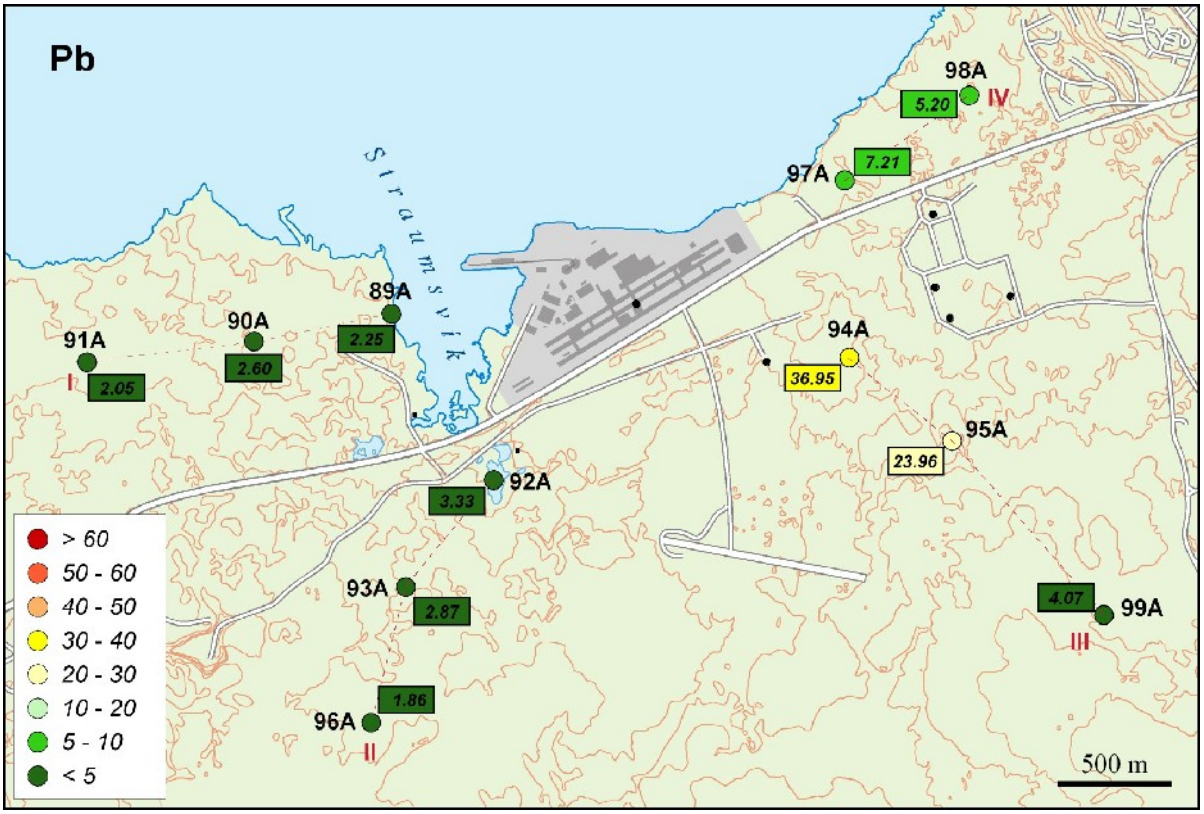


Figure 9. (A) Average lead (Pb) concentration at different distances (<3 km, 3-100 km, >100 km) from the aluminium smelter in Straumsvík for the 2000 and 2005 survey and at the industrial sites at Grundartangi and in Reyðarfjörður. - Styrkur blýs (Pb) í mosa í mismunandi fjarlægð frá álverinu í Straumsvík (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur blýs í nágrenni iðjuveranna á Grundartanga og í Reyðarfirði.

(B) Spatial distribution of lead concentration in mosses along the sampling transects <3 km to the aluminium smelter in Straumsvík in 2005. The colour scale reflects the European range of lead (Buse et al. 2003). For details see also Figure 2. - Styrkur blýs í mosa í Straumsvík og nágrenni. Litakvarði er miðaður við skýrslu Buse o.fl. frá árinu 2003. Nánari skýringar eru á 2. mynd.

4.9 Vanadium (V)

In the 2005 survey, vanadium concentration in mosses around the aluminium smelter in Straumsvík ranged from 6.79 to 18.77 µg/g and showed a clear pattern. The samples west and southwest of the smelter had concentrations between 6.79 µg/g and 13.31 µg/g but samples taken east and southeast varied between 14.04 µg/g and 18.77 µg/g (Figure 10).

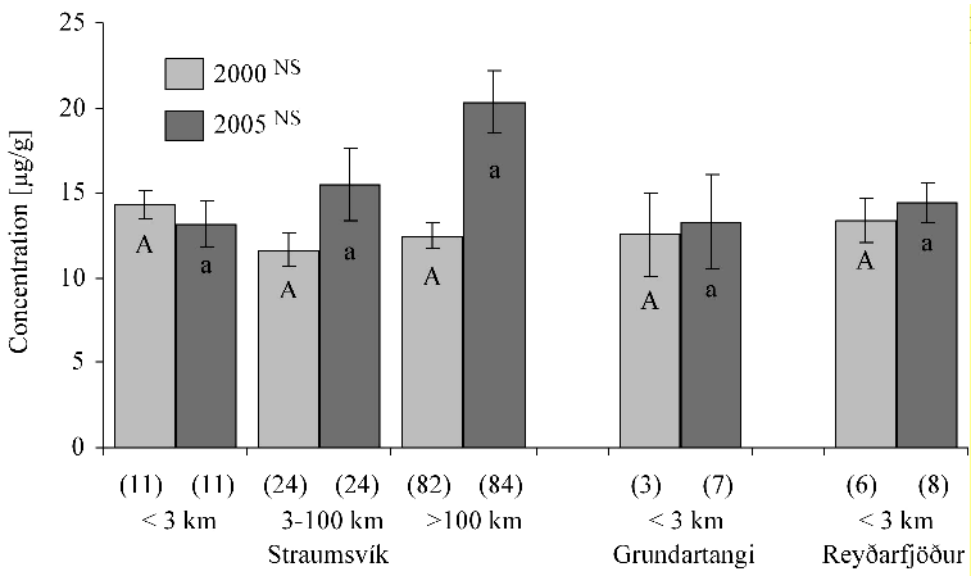
Comparison of distance classes and sites did not reveal any significant difference for either the 2000 or the 2005 survey (Figure 10). Comparison of paired values showed a significant increase in concentration between years for the distance class > 100 km, from 12.5 to 20.4 µg/g ($P < 0.001$, $n=74$). In both surveys, 2000 and 2005, the samples around the smelter ranged medium compared to all Icelandic samples (Appendix 3). It should be noted that vanadium is one of the elements which is strongly related to soil dust in Iceland and therefore the highest values are found within the volcanic active zone and in areas with high soil erosion. At the Reykjanes peninsula, the values are in general 8–14 µg/g. This range can be used as a background for Straumsvík.

The distribution pattern of vanadium in Straumsvík indicates that the smelter has little influence on the vanadium deposition in the area. This is shown by the low values of sample 89A and 92A. This is in contrast to earlier results from aluminium smelters in Norway which appear to influence vanadium deposition (Steinnes et al. 2001, Magnússon, 2002a). This discrepancy might be due to the high background values in Iceland which are likely to mask the effects from the smelter. Nevertheless, there is a difference between the western and eastern transects which cannot be explained only by differences in natural soil dust content. The other industrial activities in Straumsvík are likely to be responsible for this additional vanadium deposition.

Comparison to values for Europe is meaningless due to the high background concentration of vanadium in Iceland (Rühling and Steinnes 1998).

Vanadium (V)

A.



B.

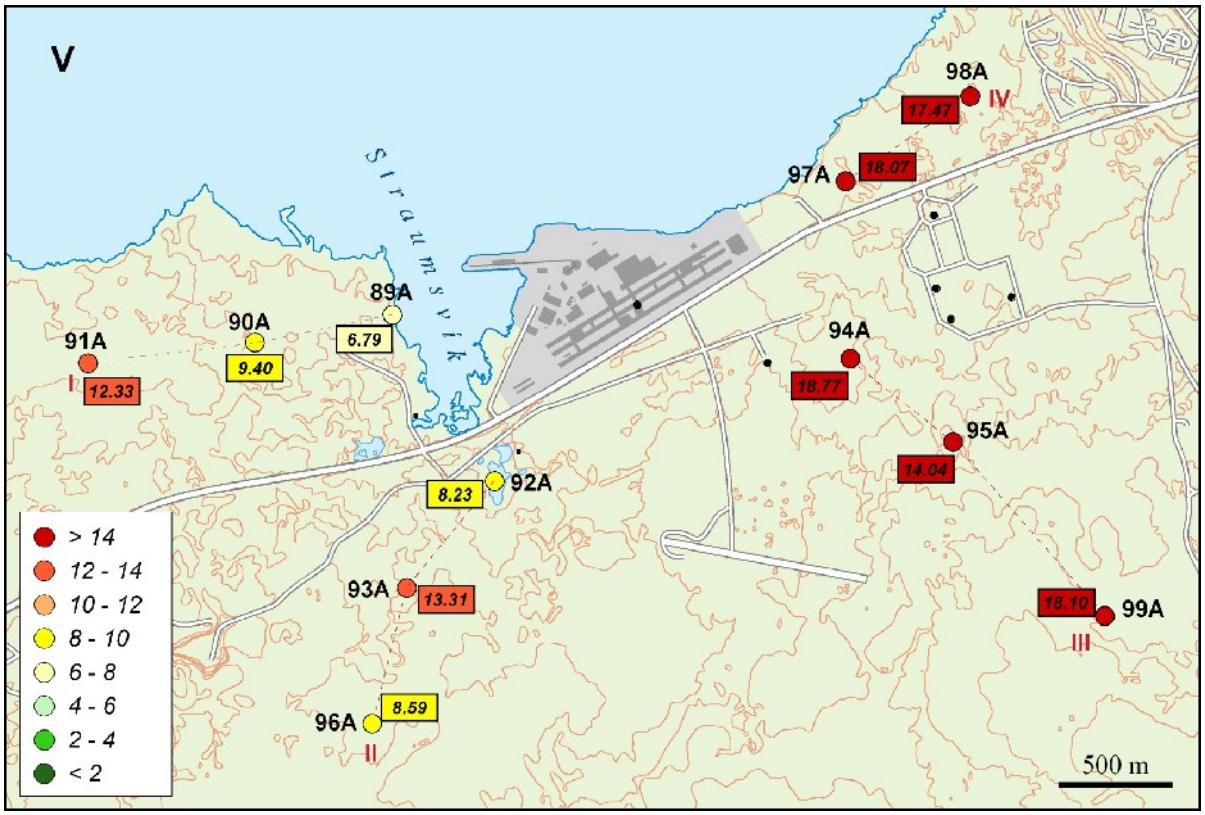


Figure 10. (A) Average vanadium (V) concentration at different distances (<3 km, 3-100 km, >100 km) from the aluminium smelter in Straumsvík for the 2000 and 2005 survey and at the industrial sites at Grundartangi and in Reyðarfjörður. - Styrkur vanadíums (V) í mosa í mismunandi fjarlægð frá álverinu í Straumsvík (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur vanadíums í nágrenni iðjuveranna á Grundartanga og í Reyðarfirði.

(B) Spatial distribution of vanadium concentration in mosses along the sampling transects <3 km to the aluminium smelter in Straumsvík in 2005. The colour scale reflects the European range of vanadium (Buse et al. 2003). For details see also Figure 2. - Styrkur vanadíums í mosa í Straumsvík og nágrenni. Litakvarði er miðaður við skýrslu Buse o.fl. frá árinu 2003. Nánari skýringar eru á 2. mynd.

4.10 Zinc (Zn)

The 2005 survey showed that in the vicinity of the Straumsvík smelter, the zinc values ranged from 29.1 to 109.9 µg/g (Figure 11). The results also showed a relatively clear concentration pattern in the area, with a maximum in samples 94A and 95A located 1000 m and 1500 m southeast of the smelter. The concentrations were lower at other sampling points, especially west and southwest of the smelter. Compared to other Icelandic samples, the concentration in Straumsvík is very high (Appendix 3).

Statistical analysis of the data from both surveys (2000 and 2005) showed that values around the smelter (<3 km) in Straumsvík were significantly higher than those further away (Figure 11). Comparison of paired values also showed that the zinc concentration had decreased with time, although only significant for distance 3-100 km (from 28.1 to 20.0 µg/g, $P < 0.001$, n=22) and > 100 km (from 28.8 to 23.4 µg/g, $P < 0.001$, n=74).

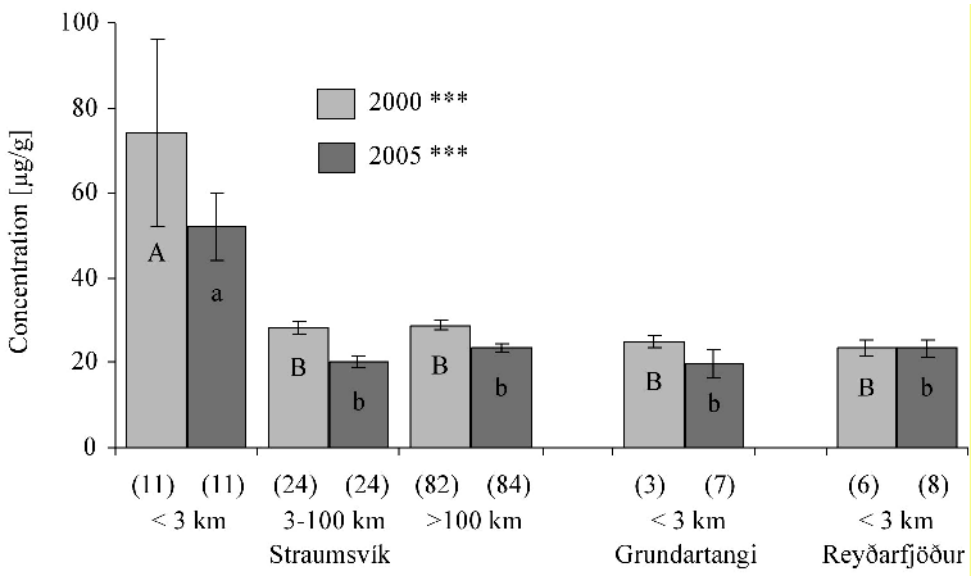
Earlier studies have shown that the natural zinc concentrations in Iceland are generally below 40 µg/g which is similar to or even lower than background values in Scandinavia (Rühling 1992, Rühling and Steinnes 1998, Magnússon 2002, Buse et al. 2003). Therefore, the high values in Straumsvík are surprising. The present distribution pattern of zinc close to the Straumsvík smelter and earlier results from Norway suggest that the smelter is not the main source (Steinnes et al. 2001, Magnússon 2002a). Instead the distribution pattern indicates that the industries east of the smelter are responsible for the high zinc deposition in the area.

In addition, investigations in Norway have not shown impacts of on aluminium smelters on zinc concentration in mosses (Steinnes et al. 2001, Magnússon 2002a). The industrial area contains galvanising and other industries working with high amounts of zinc which are probably responsible for the high zinc deposition in transect III. Therefore, higher zinc concentrations in samples 94A and 95A caused by these industries.

The observed decrease in background concentration of zinc in Iceland in general between 2000 and 2005 indicates a decrease in long range transport from abroad during that period.

Zinc (Zn)

A.



B.

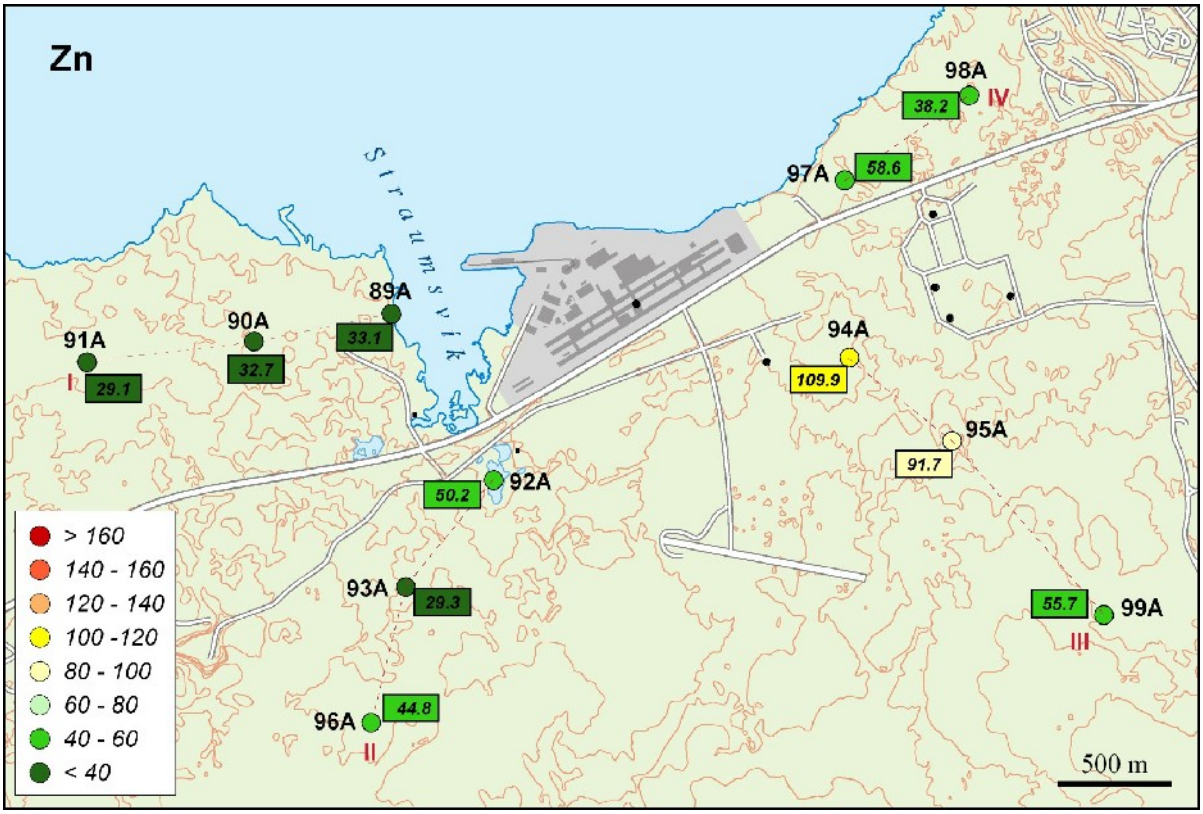


Figure 11. (A) Average zinc (Zn) concentration at different distances (<3 km, 3-100 km, >100 km) from the aluminium smelter in Straumsvík for the 2000 and 2005 survey and at the industrial sites at Grundartangi and in Reyðarfjörður. - Styrkur sinks (Zn) í mosa í mismunandi fjarlægð frá álverinu í Straumsvík (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur sinks í nágrenni iðjuveranna á Grundartanga og í Reyðarfirði.

(B) Spatial distribution of zinc concentration in mosses along the sampling transects <3 km to the aluminium smelter in Straumsvík in 2005. The colour scale reflects the European range of zinc (Buse et al. 2003). For details see also Figure 2. - Styrkur sinks í mosa í Straumsvík og nágrenni. Litakvarði er miðaður við skýrslu Buse o.fl. frá árinu 2003. Nánari skýringar eru á 2. mynd.

4.11 Sulphur (S)

In 2005, sulphur concentration in mosses in the vicinity of the Straumsvík smelter varied from 534 to 774 µg/g and showed a clear distribution pattern with the highest values occurring close to the smelter (Figure 12). Compared to the other samples around Iceland the samples close to the factory are rather high (Appendix 3).

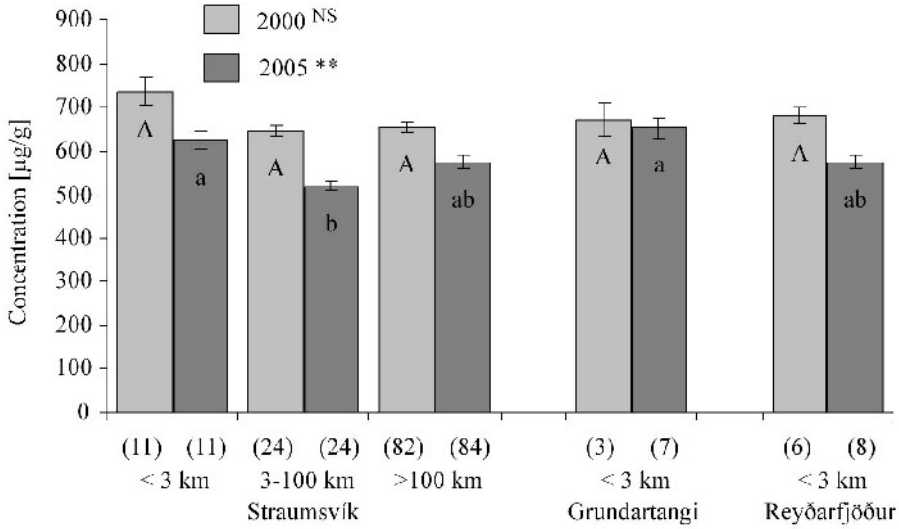
In 2000, there were no significant differences between the distance classes (Figure 12). This changed in 2005 as the Grundartangi site (< 3 km) was significantly higher than the distance class 3-100 km. All distance classes and sites, compared and tested by paired values, showed a significant decrease between 2000 and 2005; in Straumsvík from 737 to 625 µg/g, ($P < 0.01$, n=11); within the class 3-100 km from 647 to521 µg/g ($P < 0.001$, n=22); at > 100 km from 655 to 576 µg/g, $P < 0.001$, n=74; at Reyðarfjörður from 682 to 575 µg/g ($P < 0.05$, n=4).

As sulphur is not measured in the European wide programme, it is not possible to give a statement about the background and range of concentration in other European countries. However, other studies have successfully used sulphur contents in mosses to identify pollution sources (Äyräs, Pavlov and Reimann 1997, Reimann et al. 2001). Results of these studies show that maps of sulphur concentrations are fuzzier than those of other elements.

The gradients and concentrations in the present study show that the aluminium smelter has significant influence on the sulphur concentration in the moss samples. The strongest influence seems to be very close to the smelter. However, it can not be excluded that the high value of sample 94A is also due to other emission sources in the area. These results are similar to those of the 2000 survey for the Straumsvík site and are also in accordance with to results from the 2005 survey at the Grundartangi industrial site (Magnússon and Thomas 2007).

Sulphur (S)

A.



B.

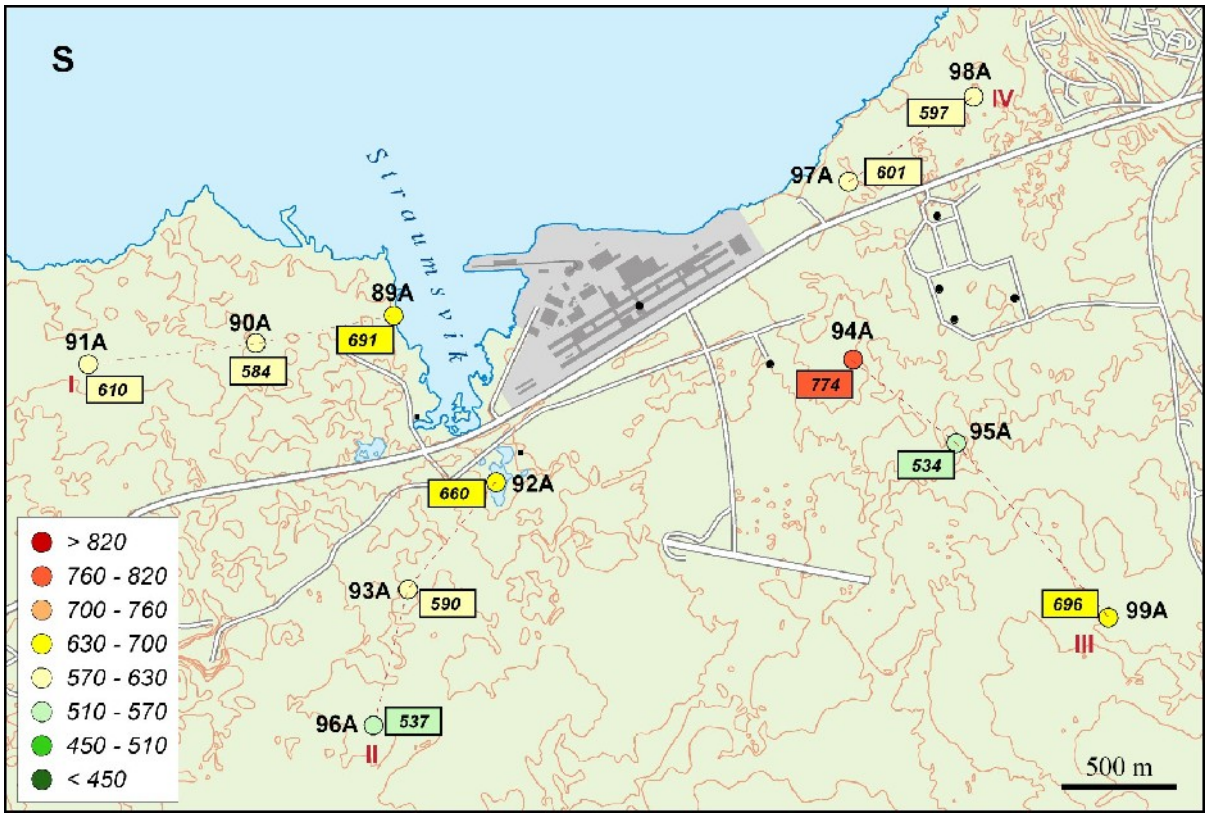


Figure 12.*(A) Average sulphur (S) concentration at different distances (<3 km, 3-100 km, >100 km) from the aluminium smelter in Straumsvík for the 2000 and 2005 survey and at the industrial sites at Grundartangi and in Reyðarfjörður.* - Styrkur brennisteins (S) í mosa í mismunandi fjarlægð frá álverinu í Straumsvík (<3 km, 3–100 km, >100 km) árin 2000 og 2005. Til samanburðar er einnig sýndur styrkur brennisteins í nágrenni iðjuveranna á Grundartanga og í Reyðarfirði.

(B) Spatial distribution of sulphur concentration in mosses along the sampling transects <3 km to the aluminium smelter in Straumsvík in 2005. For details see also Figure 2. - Styrkur brennisteins í mosa í Straumsvík og nágrenni. Nánari skýringar eru á 2. mynd.

5 CONCLUSIONS

The following conclusions may be made on the basis of the study:

The concentration of most of the measured elements is higher in moss samples from around the Straumsvík smelter than from background areas. The effects differed among elements; they were highest for lead, nickel, arsenic and zinc but lowest for vanadium and iron.

The distribution pattern of the measured elements around the Straumsvík smelter is mainly of two types which indicates two main emission sources. On one hand is a distribution pattern of high concentration close to the Straumsvík smelter, which strongly suggests the smelter as a main source; this applies to arsenic, nickel and sulphur. On the other hand is a distribution pattern to the east and southeast of the smelter, which suggests other industries in the area as a main source; this applies to lead, zinc, copper, chromium, iron and vanadium. The distribution patterns for cadmium and mercury indicate effects from both sources.

According to the background values in Iceland and northern Europe, the concentrations of arsenic and nickel emitted from the smelter are relatively high in the area. Sulphur, which is also emitted from the smelter, was found in significantly higher concentrations close to the smelter than in the background area but was however not the highest in the country.

The deposition of air pollutants changed over time. Close to the smelter the concentration of nickel and sulphur decreased significantly between 2000 and 2005. The same was also true for lead, copper and chromium. None of the elements increased in concentration during this period. This indicates that pollution from heavy metals and sulphur has decreased in the Straumsvík area between 2000 and 2005.

The deposition also changed on a country wide basis with time. The concentrations of nickel, iron, and vanadium increased but mercury, zinc, lead, and sulphur decreased between 2000 and 2005. The concentration of nickel, iron and vanadium is generally high in Iceland and is related to aeolian dust caused by soil erosion and reflects the composition of the bedrock and the volcanic thepra. Increased concentrations of these elements are therefore more likely reflecting changes in dust content rather than increased pollution. Mercury, zinc and lead are generally in low background concentration in Iceland and no local emission sources are known. Therefore, the decrease observed in concentrations of these elements between 2000 and 2005 indicates a decline in long-distance transport. This is probably also the main reason for the decrease in concentration of sulphur.

Results of these types of study can be used to identify emission sources, quantify transport into ecosystems and to examine changes in deposition load in time and space. However, they are not relevant for assessment of damage to plants or ecosystems. For that, other types of studies are needed. However, the present results from Straumsvík and comparison to other sites in Iceland and northern Europe clearly show that the heavy-metal load is comparatively high close to the Straumsvík smelter; especially 1,0–1,5 km east and southeast of the smelter. According to concentration pattern of the measured elements and the emission sources the pollution load is probably higher from the industrial area to the east of the smelter than from the smelter itself.

5.1 Acknowledgement

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APENDICES

APPENDIX 1: Industrial activities in the surroundings of the aluminium smelter in Straumsvík *(revised from Magnússon 2002a)*.

Yfirlit yfir iðnaðarstarfsemi í nágrenni álversins í Straumsvík. Endurskoðaðar upplýsingar frá Sigurði H. Magnússyni (2002a).

Company *Fyrirtæki*	Location *Staðsetning*	Description *Lýsing*	Type of possible discharge *Líkleg losun*
Geymslusvæðið ehf.	Centre of the area about 600 m south of the smelter. *Um 600 m suður af álveri.*	Waste yard for cars etc.[1)] *Geymslusvæði fyrir bílhræ o.fl.[1)]*	Very low.[10)] *Óveruleg.*[10)]
Gasaflsstöð Landsvirkjunar.	About 600 m southeast of the smelter. *Um 600 m suðaustan við álver.*	Gas bottle station and storage. [1)] *Gasaflsstöð.[1)]*	Unknown. *Óþekkt.*
Fura ehf., Hringhella 3.	About 1400 m east of the smelter. *Um 1400 m austan við álver.*	Scrap iron processing, running since 1989. In 2000 reception of lead batteries was terminated but slicing and grinding of tires started.[2)] *Brotajárnsvinnsla starfrækt frá 1989, brotajárn tætt niður. Frá 2000 hafa dekk einnig verið tætt niður en móttöku rafgeyma var þá hætt.[2)]*	Metal dust. *Málmryk.*
Hlaðbær Colas, Hringhella 6.	About 1350 m east of the smelter. *Um 1350 m austan við álver.*	Asphalt plant, running since 1987.[3)] Between 2000 and 2005 the production increased from 100000 to 140000 tons/year.[6)] *Malbikunarstöð starfrækt frá 1987.[3)] Framleiðsla var 100.000 tonn/ári árið 2000 en 140.000 tonn/ári árið 2005.*[6)]	Stone dust from Icelandic basalt and imported granite.[3)] Gases from asphalt and from burning of diesel fuel.[6)] *Steinryk af innlendu basalti og innfluttu graníti [3)], gufa frá biki og lofttegundir v. brennslu á dísel- og skipagasolíu.*[6)]
Steypustöðin MEST, Hringhella 2. Previously: Steinsteypan ehf.	About 1650 m east of the smelter *Um 1650 m austan við álver*	Concrete production, running since May 1995.[4)] *Steypustöð, starfrækt frá maí 1995.[4)]*	Dust of cement and stone. *Sementsryk og steinryk.*
Verkvík-Sandtak, Rauðhella 3. Previously: Sandtak.	About 1400 m east of the smelter. *Um 1400 m austan við álver.*	Sandblasting and metal coating, running since 1996.[3)] In recent years also a construction company.[7)] *Sandblástursfyrirtæki starfrækt frá 1996 en auk þess hefur þar einnig verið unnið að sinkhúðun [5)] og á seinni árum einnig starfrækt byggingafyrirtæki á sömu lóð.[7)]*	Dust of stone, rust, old paint, zinc etc.[3)] *Steinryk, ryk af gamalli málningu, sinki o.fl. [7)]*
Blendi, Íshella 5.	About 1100 m east of the smelter. *Um 1100 m austan við álver.*	Recycling of anodes from aluminium smelters, running since 2001.[8)] *Endurvinnsla á rafskautum fyrir álver, starfrækt frá 2001.[8)]*	Dust – only on a small scale.[8)] *Ryk – aðeins í litlum mæli.[8)]*

Zinkstöðin, Berghella 2. Previously: Stekkur.	About 1200 m east of the smelter. *Um 1200 m austan við álver.*	Hot dip galvanizing, running from March 2003.[9)] *Heitgalvanisering, starfrækt frá mars 2003.*[9)]	Gases and zinc dust originating from the galvanizing process.[9, 10)] *Gufur og sinkryk, aðallega frá málminum sem verið er að húða með.*[9, 10)]
Gámaþjónustan hf.	About 1200 m east of the smelter. *Um 1200 m austan við álver.*	Transfer station for industrial waste, running since 2001.[10, 11)] *Umhleðslustöð fyrir úrgang frá fyrirtækjum, starfrækt frá 2001.*[10, 11)]	Unknown. *Óþekkt.*
Other activities. *Önnur starfsemi.*		Small metal industries etc., disturbance from construction of roads and buildings.[10)] *Á svæðinu eru ýmis bílgreinafyrirtæki og málmsmíðafyrirtæki. Miklar framkvæmdir við gatnagerð og nýbyggingar.*[10)]	Unknown. *Óþekkt.*

Personal communication – *munnlegar upplýsingar*.
[1)] Sigurður Haraldsson, 2002; [2)] Haraldur Ólafsson, 2002, 2007; [3)] Sigurður Sigurðsson, 2002; [4)] Hannes Sigurgeirsson, 2002; [5)] Einar Einarsson, 2002; [6)] Sigþór Sigurðsson, 2007; [7)] Gunnar Árnason, 2007; [8)] Valdimar Jónasson, 2007; [9)] Ragnar Pálmason, 2007; [10)] Páll Stefánsson, 2007; [11)] Arngrímur Sverrisson, 2007.

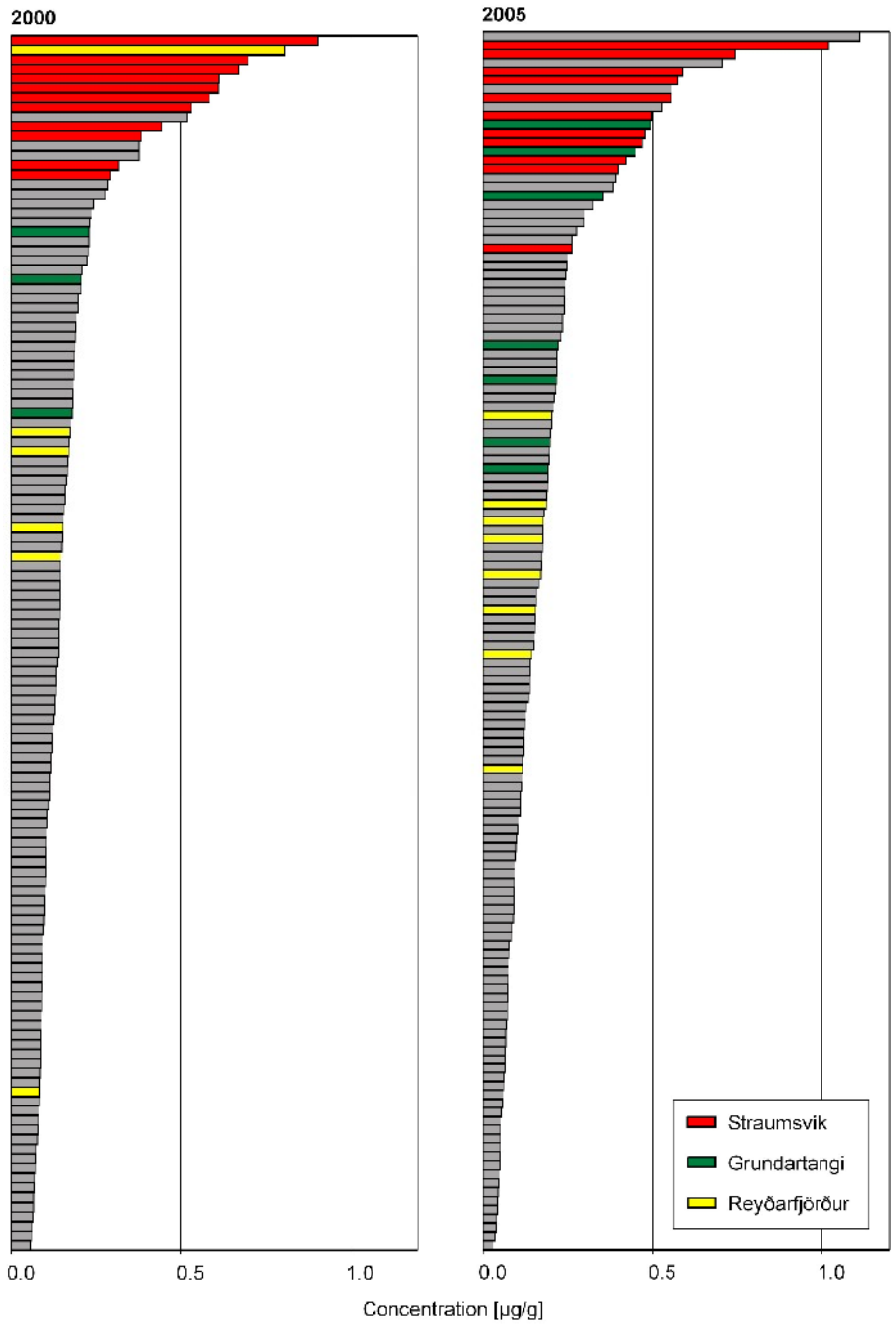
APPENDIX 2: Quantification Limits
Magngreiningarmörk

Substance *Efni*	Quantification Limit µg/g *Magngreiningarmörk*
As	0.00810
Cd	0.00075
Cr	0.00945
Cu	0.00075
Fe	0.03150
Hg	0.00315
Ni	0.03150
Pb	0.00060
S	5.10000
V	0.44550
Zn	0.05850

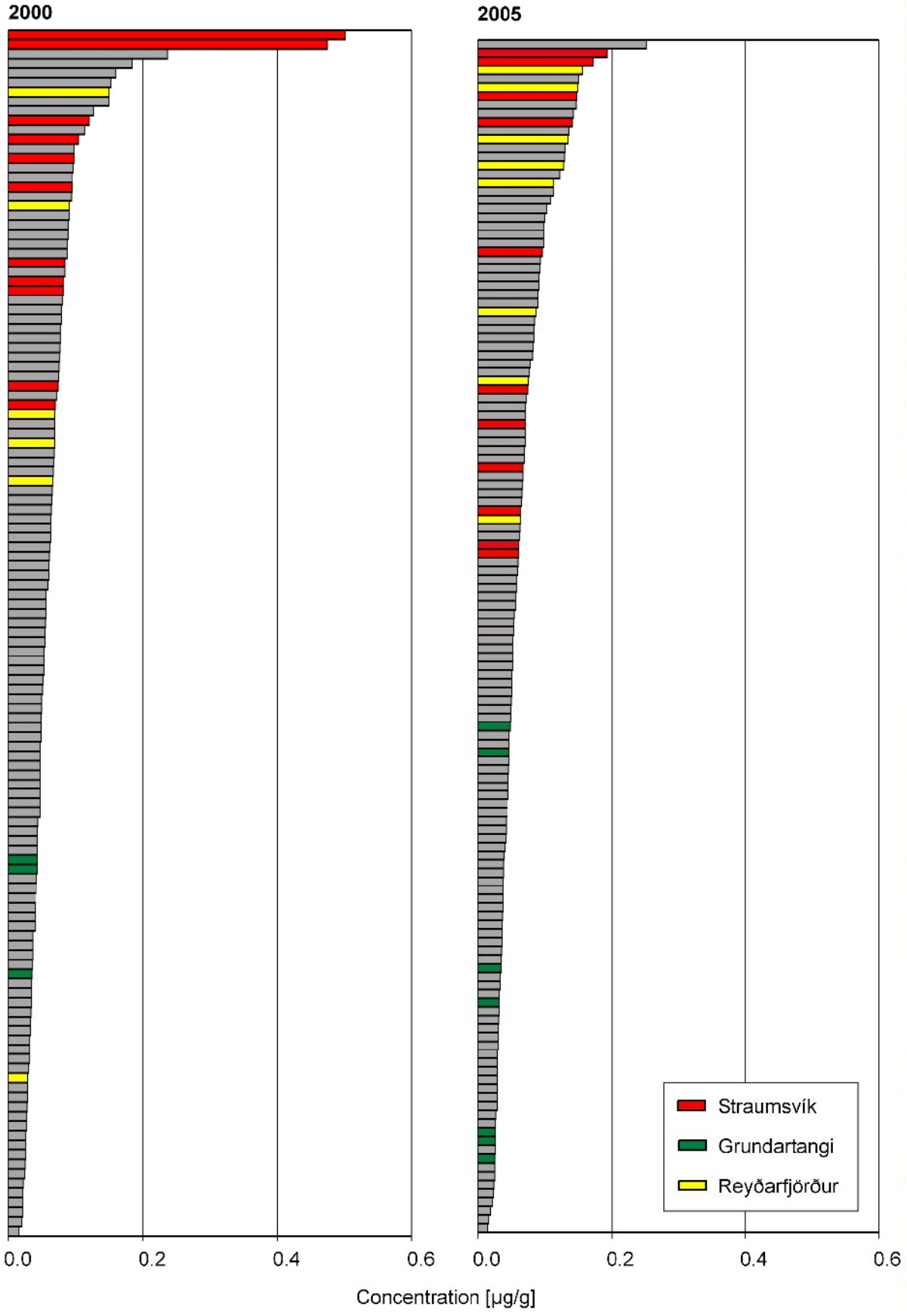
APPENDIX 3: Concentration in samples of the 2000 and 2005 Icelandic moss survey
Styrkur efna í mosasýnum frá 2000 og 2005

Concentration of heavy metals and sulphur in moss samples collected throughout Iceland in the 2000 and 2005 moss survey, shown in a descending order. The samples 3 km around the aluminium smelter in Straumsvík (red), ferro-silicon plant and aluminium smelter at Grundartangi (green) and smelter site in Reyðarfjörður (yellow) are marked. – *Styrkur þungmálma og brennisteins í mosa sem safnað var víðsvegar um land árin 2000 og 2005. Sýnum er raðað eftir magni viðkomandi efnis. Sýni sem safnað var í nágrenni (< 3 km) verksmiðjanna eru merkt með mismunandi litum: Straumsvík (rauð), verksmiðjur á Grundartanga (græn), fyrirhugað álver í Reyðarfirði (gul).*

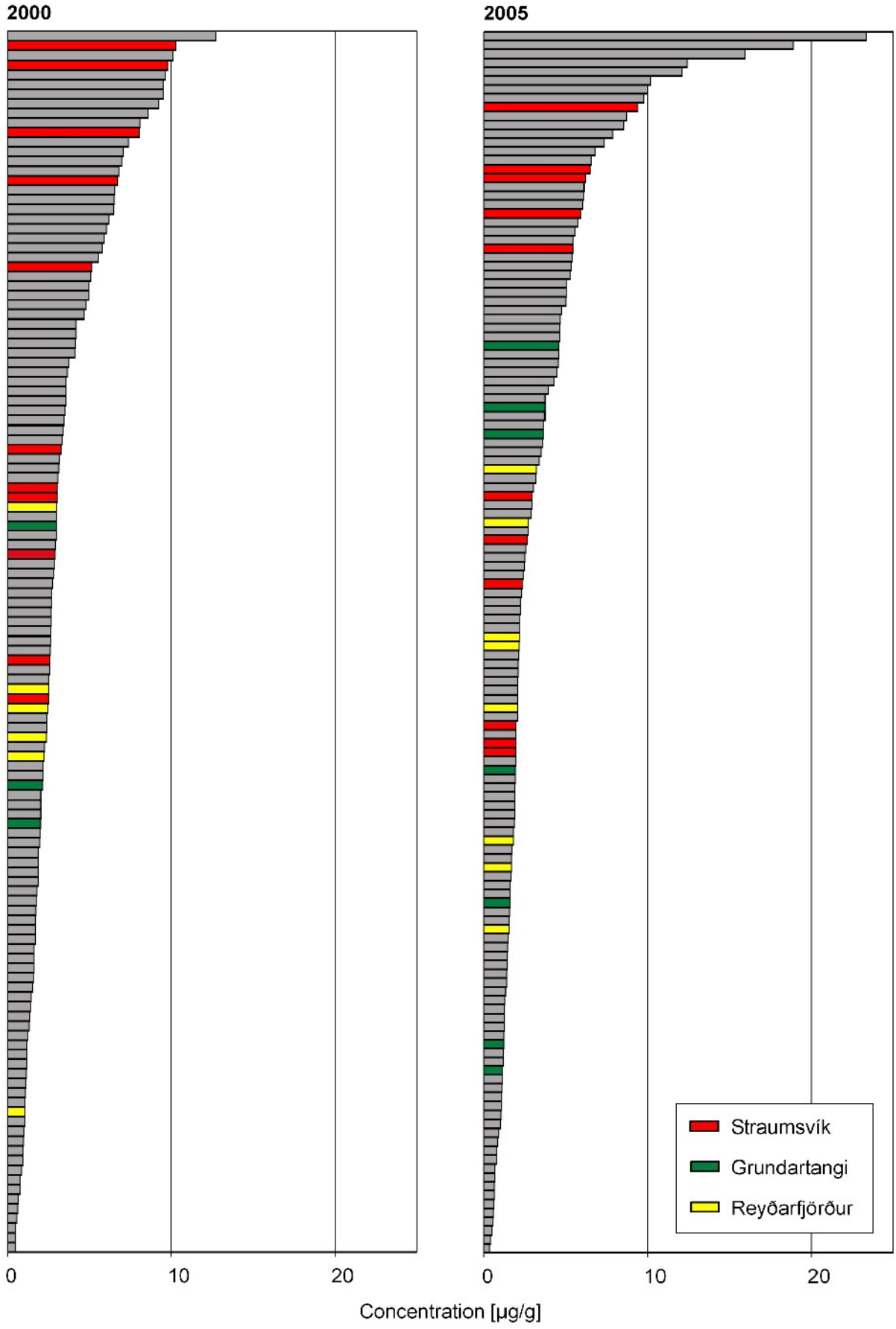
Arsenic (As)



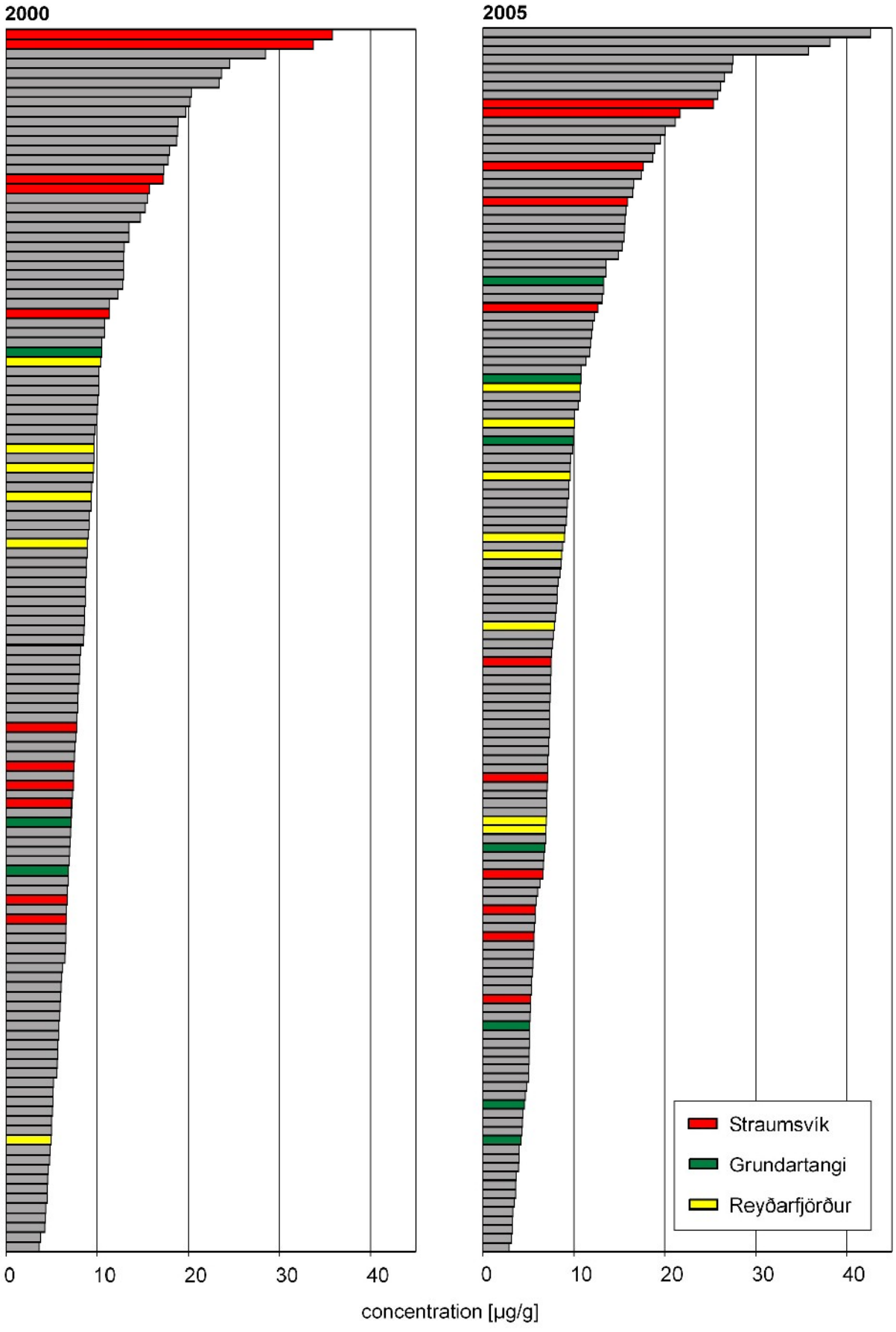
Cadmium (Cd)


2000
2005
Straumsvík
Grundartangi
Reyðarfjörður
0.0
0.2
0.4
0.6
Concentration [µg/g]

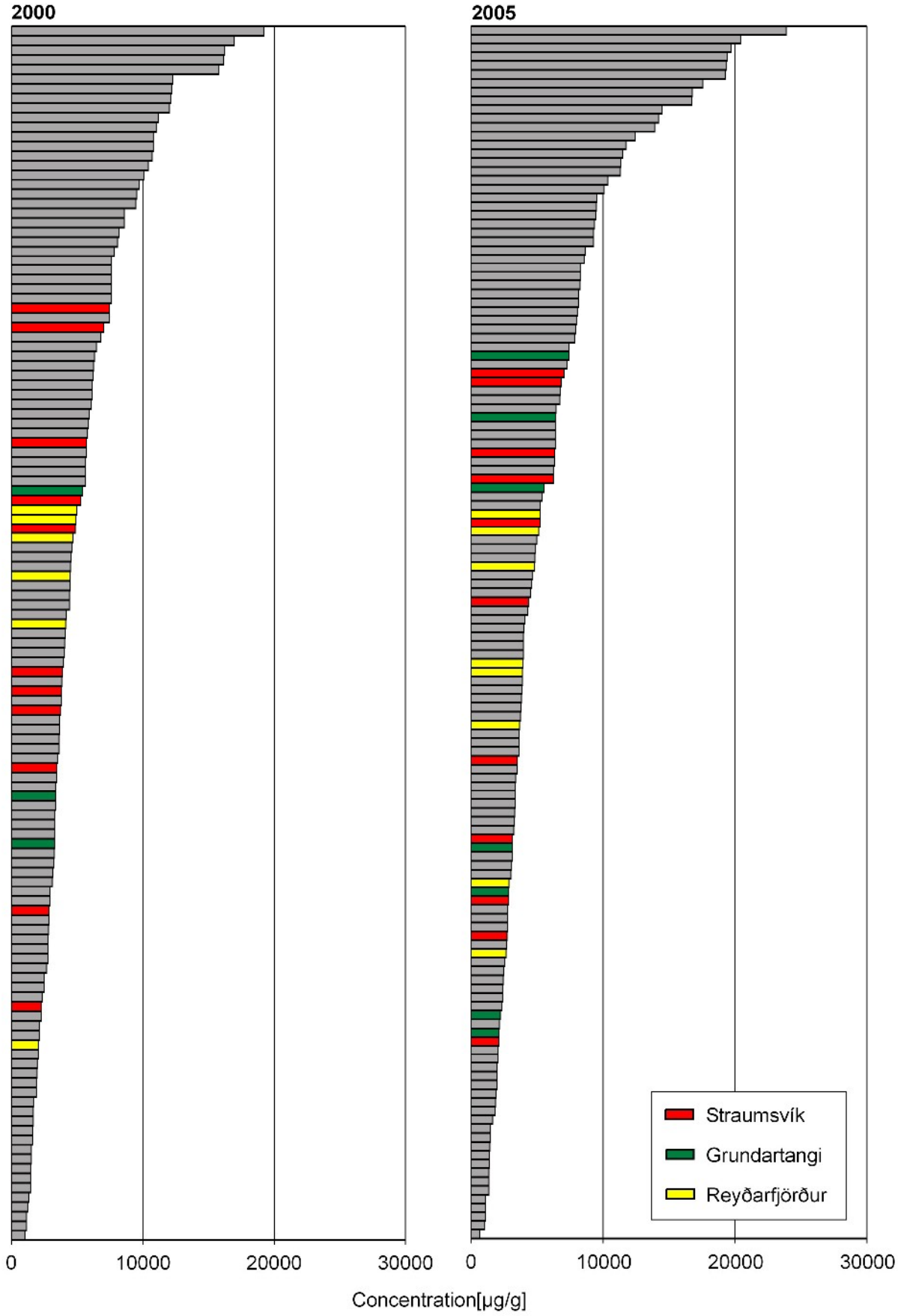
Chromium (Cr)


2000
2005
0
10
20
0
10
20
Straumsvík
Grundartangi
Reyðarfjörður
Concentration [µg/g]

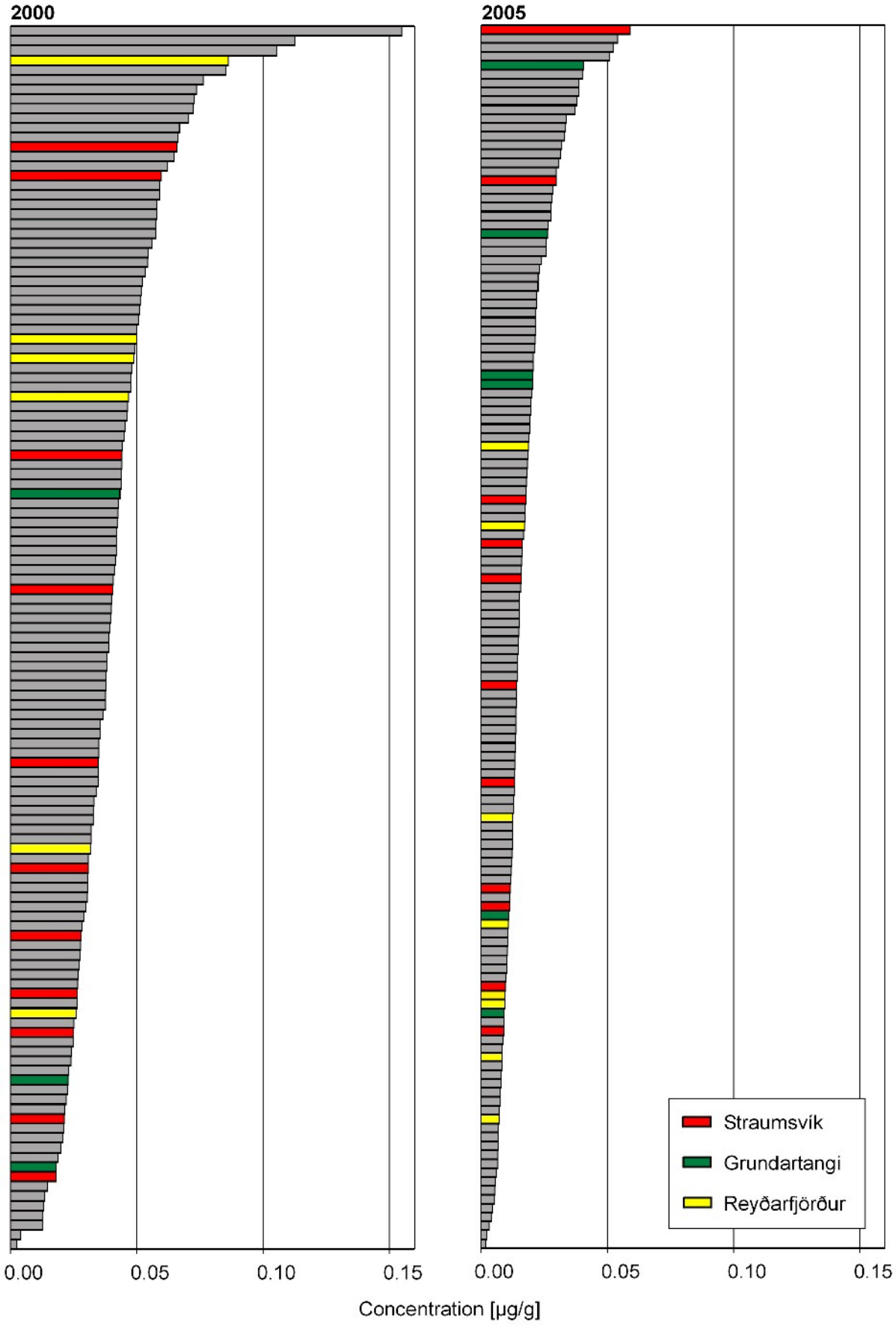
Copper (Cu)


2000
2005
0
10
20
30
40
concentration [µg/g]
Straumsvík
Grundartangi
Reyðarfjörður

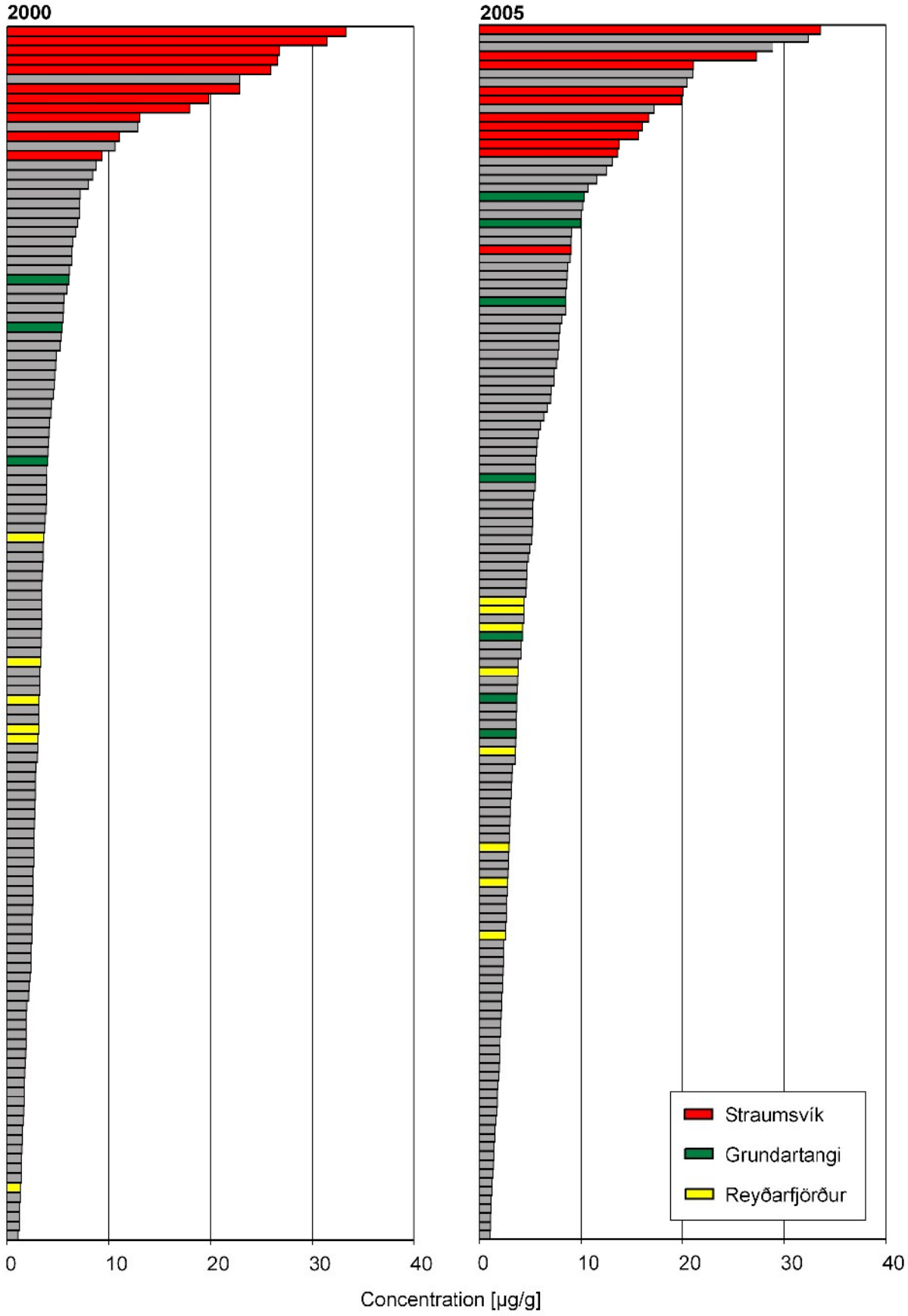
Iron (Fe)


2000
2005
0
10000
20000
30000
Concentration[µg/g]
Straumsvík
Grundartangi
Reyðarfjörður

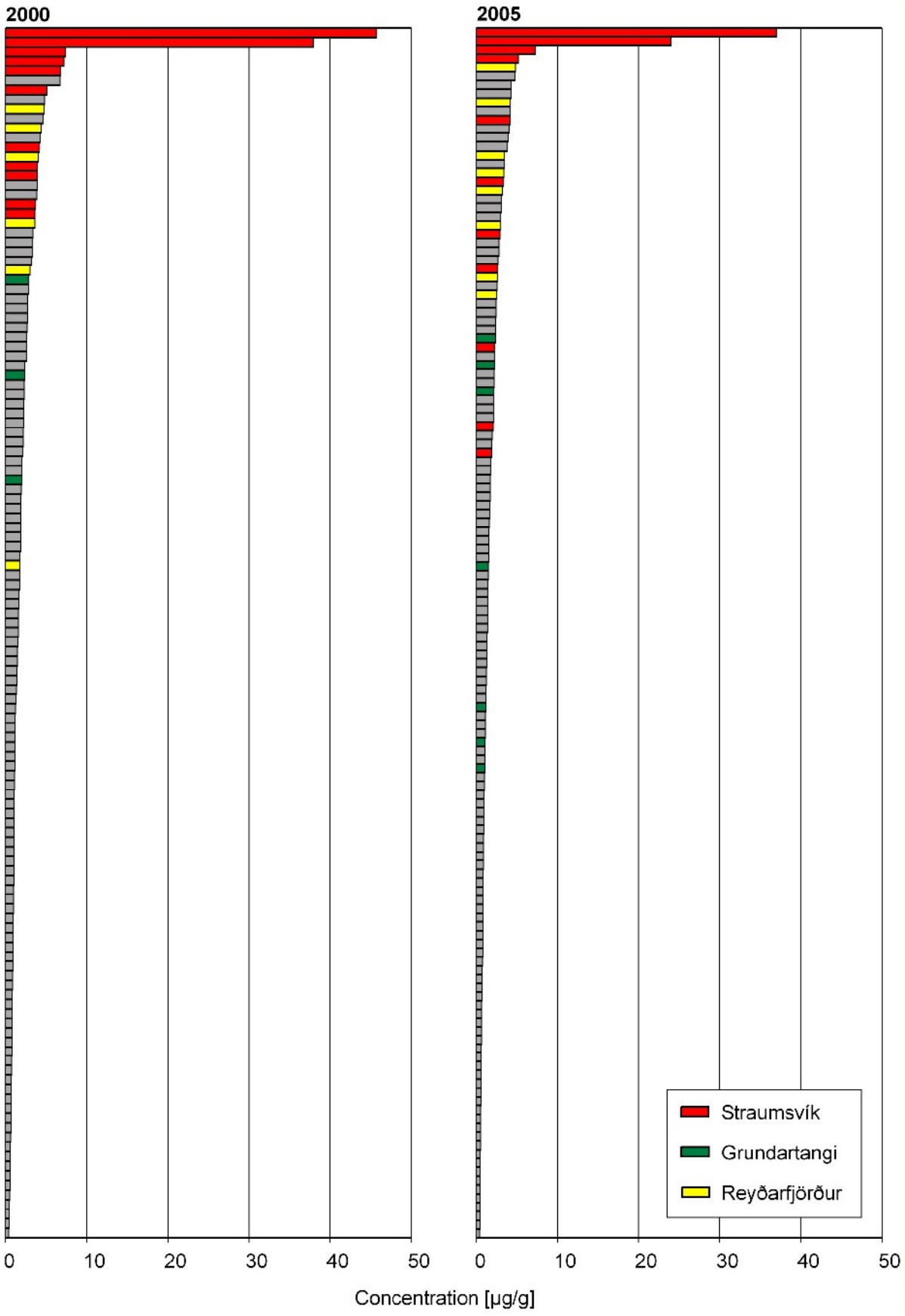
Mercury (Hg)


2000
2005
0.00
0.05
0.10
0.15
Straumsvík
Grundartangi
Reyðarfjörður
Concentration [µg/g]

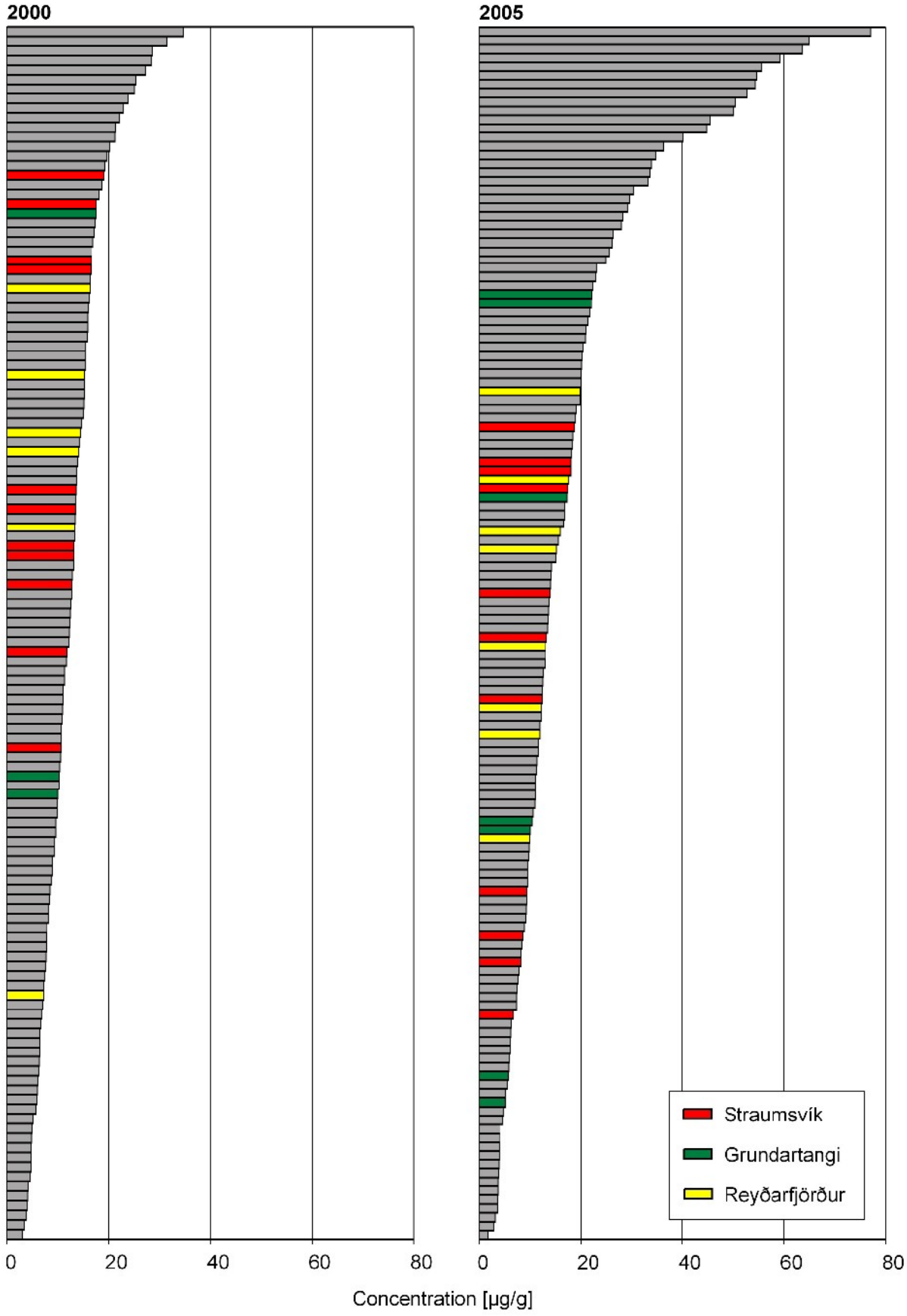
Nickel (Ni)


2000
2005
0
10
20
30
40
Straumsvík
Grundartangi
Reyðarfjörður
Concentration [µg/g]

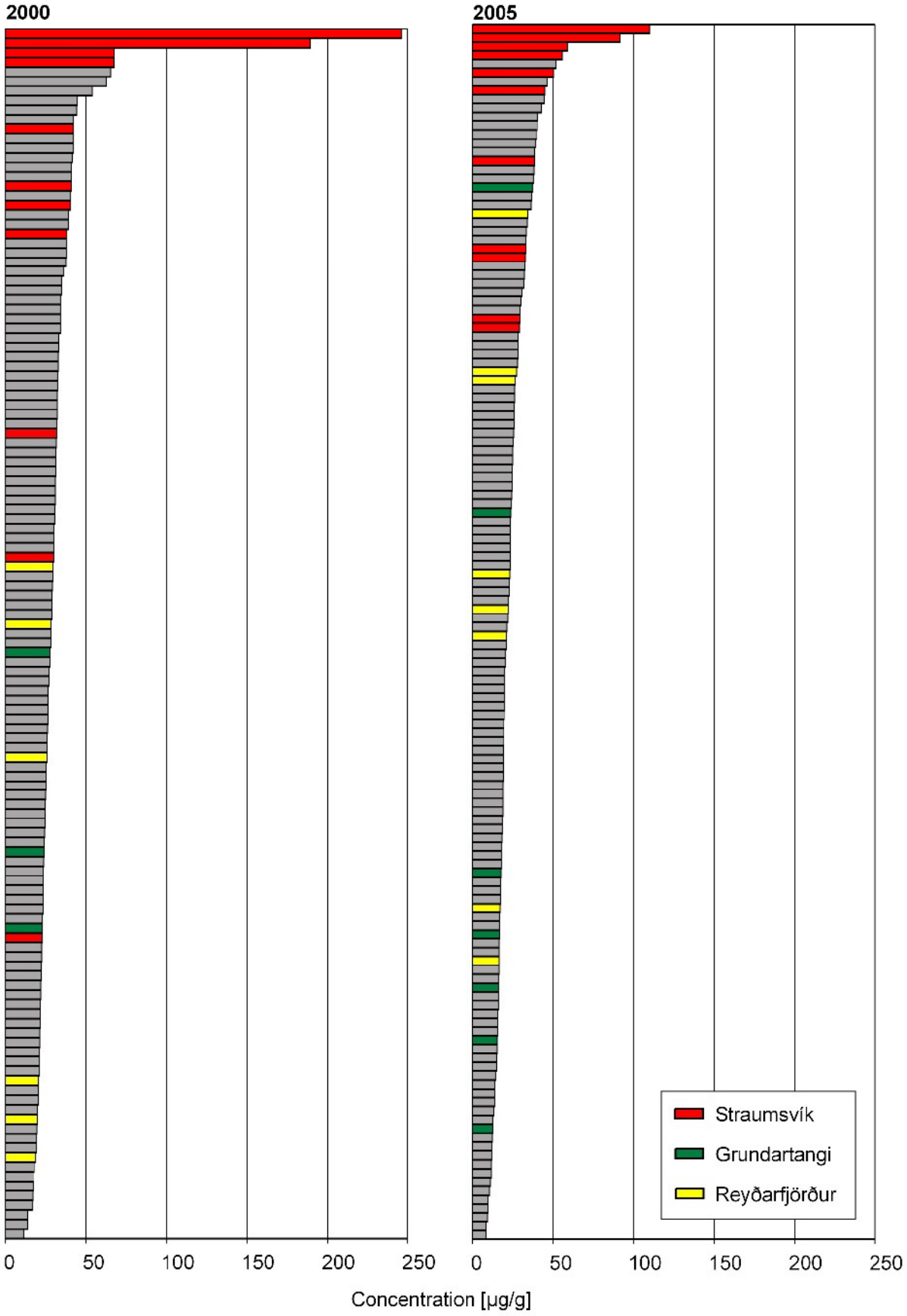
Lead (Pb)


2000
2005
Straumsvík
Grundartangi
Reyðarfjörður
0
10
20
30
40
50
Concentration [µg/g]

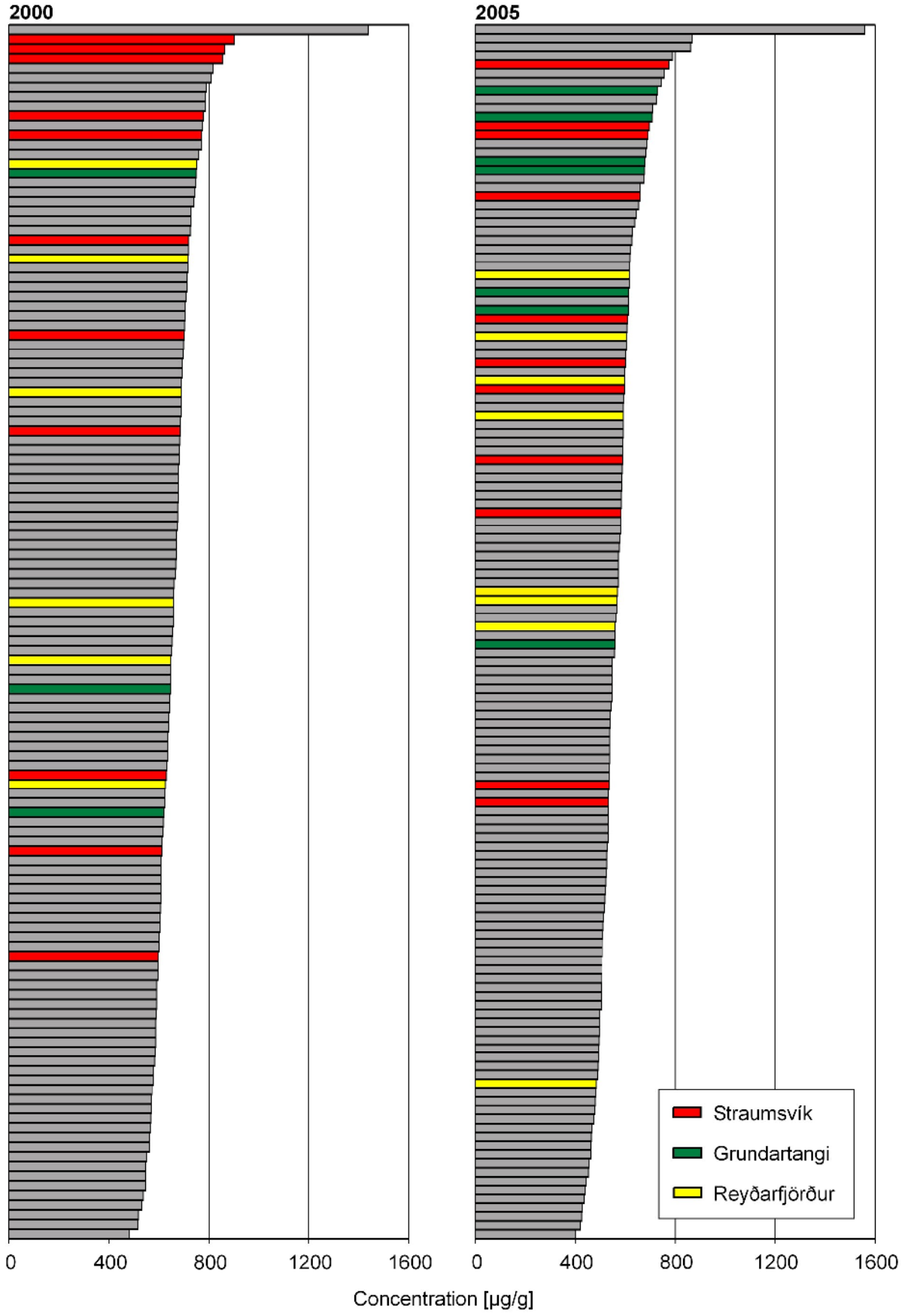
Vanadium (V)


2000
2005
0
20
40
60
80
Straumsvík
Grundartangi
Reyðarfjörður
Concentration [µg/g]

Zinc (Zn)


2000
2005
Straumsvík
Grundartangi
Reyðarfjörður
0
50
100
150
200
250
Concentration [µg/g]

Sulfur (S)


2000
2005
0
400
800
1200
1600
Straumsvík
Grundartangi
Reyðarfjörður
Concentration [µg/g]