Environmental monitoring of fish in the Paz watercourse

A sub-report of the InterReg project '*Development and implementation of an integrated environmental monitoring and assessment system in the joint Finnish, Norwegian and Russian border area*' (2003-2006).

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Summary

The ecology, pathology and heavy metal contaminations of fish in the Inari-Paz watercourse have been explored as a part of the EU-InterReg project 'Development and implementation of an environmental monitoring and assessment system in the joint Finnish, Norwegian and Russian border area' (2003-2006). The watercourse is located in the vicinity of the Petchenganikel metallurgic smelters which are the source of a large output of heavy metals to the environment. The study included a gradient of six lakes located with increasing distance from the smelters, including Kuetsjarvi and Rajakoski in Russia, Lake Inari in Finland, and Skrukkebukta and Vaggatem in Norway, as well as a reference lake locality (Stuorajavri) in the Kautokeino-Alta watercourse, Norway. The project has been carried out in close cooperation between the Institute of North Industrial Ecology Problems, Kola Science Centre, Apatity, and the Norwegian College of Fishery Science, University of Tromsø.

The studied lakes have high fish diversity for a subarctic region, composing complex and interactive food webs including several piscivorous species. Whitefish, perch, pike and brown trout were the most important fish species in the lakes, together with vendace which is a non-native species that has been introduced to the Inari-Paz watercourse. The Petchenganikel metallurgic industry appeared to have a large influence on the heavy metal contaminations in freshwater fish in the vicinity of the smelters. The highest concentrations of most heavy metals were observed in fish from Kuetsjarvi, whereas the contamination levels in fish tissue rapidly decreased with increasing distance to the smelters. For most heavy metals the highest contamination levels were observed in internal organs including liver, kidney and gills, and the lowest levels in muscle tissue. Fish from Kuetsjarvi exhibited a high prevalence of pathological abnormalities in internal organs, comprising deformation of gonads, kidney stones and other changes in kidneys, liver and gills. The incidence of pathological disorders decreased with increasing distance to the smelters, exhibiting a strong correlation with the contamination levels of most heavy metals and suggesting a causal relationship between fish pathology and heavy metal pollution. The fish population ecology studies furthermore suggested life-history responses to the pollution impacts in Kuetsjarvi in terms of early maturation, diminished growth rates and short longevity, especially in whitefish.

Heavy metals are regarded as potential hazards that can endanger both animal and human health, and knowledge of their concentrations in fish is important both with respect to nature monitoring and management of freshwater fish populations for human consumption. Based on the findings on the present study, a continued monitoring of fish in the Inari-Paz watercourse with respect to heavy metal contamination, population ecology and fish pathology is recommend as a part of the planned monitoring program for the border areas. The monitoring studies of fish should be carried out with a maximum of three years intervals along a spatial gradient of four lake localities with increasing distance to the smelters (Kuetsjarvi, Skrukkebukta, Vaggatem and Lake Inari). Analyses should comprise selected parameters of fish ecology and pathology as well as heavy metal analyses of muscle, liver, gills and kidney samples from whitefish, perch and pike. The importance of continued environmental monitoring of the fish populations in the Inari-Paz watercourse can be summarized as: 1) freshwater fish are important resources for recreational, subsistence and commercial exploitation and human consumption in the watercourse; 2) fish are sensitive and conspicuous indicators of the environment quality; 3) severe impacts of the metallurgic industry have already been documented to occur; and 4) a renovation program for the Pechenganikel smelters is expected to result in a significant decrease in the heavy metal pollution impacts in the watercourse, and potential effects can efficiently be monitored and documented by the suggested studies of fish.

1. Introduction

Freshwater systems are focal points for pollution, draining the surrounding landscape and acting as sinks for environmental contaminants that may end up in fish and even in humans that consume the fish. An important part of the EU-InterReg project "Development and implementation of an environmental monitoring and assessment system in the joint Finnish, Norwegian and Russian border area" has therefore been related to the freshwater ecosystems and their fish communities, including an evaluation of potential pollution impacts from metallurgic industry and other anthropogenic activities in the region.

The Inari-Paz watercourse is the central freshwater system and a key characteristic of the border area between Finland, Norway and Russia, covering an area of approx. 1250 km^2 and with a catchment area of more than 18000 km^2. It originates in Finland, runs into Russia and then forms the border between Norway and Russia over a distance of about 120 km. The watercourse has rich natural resources, constituting a subarctic system with high biodiversity and production of fish and other aquatic organisms. Fish resource utilisation includes commercial, subsistence and recreational fishery, with an annual harvest ranging from 200 to 600 tons of fish over the last decades (Kristoffersen & Sterud 1985, Mutenia & Ahonen 1990, Salonen 1998). The watercourse is located in the vicinity of the Petchenga-Nikel metallurgic enterprises, and the lower part of the watershed drains the Nikel smelters directly through the lake Kuetsjarvi. Emission of heavy metals from mining activity, smelters and industry is the source of serious environmental pollution (Kelly 1988). High levels of heavy metal contamination have been recorded in water and sediments in the vicinity of the Nikel smelters (Traaen et al. 1991, Duvalter 1992, 1994, Rognerud et al. 1993, Moiseenko et al. 1995), possessing a threat to fish and other biota (e.g. Lukin and Kashulin 1991, Nøst et al. 1991, 1997, Amundsen et al. 1993, 1997, Kashulin et al. 1999, 2003, Lukin et al. 2003), and potentially also a health problem for humans consuming fish from the watercourse. The contamination of heavy metals in aquatic ecosystems has received considerable attention due to their toxicity and accumulation in biota (Mance 1987, Mason 1991). Some of these elements are toxic to living organisms even at quite low concentrations, whereas other are biologically essential and natural constituents of the aquatic ecosystems, and only become toxic at very high concentrations. In fish, the toxic effects of heavy metals may influence physiological functions, individual growth rates, reproduction and mortality (Mance 1987, Sorensen 1991, Woodward et al. 1994, 1995, Farag et al. 1994, 1995), and ecological effects may therefore be found both at the individual, population and community levels. Other environmental impacts in the Inari-Paz watercourse include seven large hydroelectric dams constructed in the period from 1951-1978, which have had a major influence on the physical characteristics of the system. Furthermore, several exotic fish species have during the last decades been introduced into the watercourse, representing a threat for the natural biodiversity (Amundsen et al. 1999, Bøhn & Amundsen 2001, Salonen et al. 2006).

A central part of the InterReg project has been to perform baseline biological studies to provide a necessary status and develop a monitoring system for the ecological situation in the Inari-Paz watercourse. In this respect, a gradient of six lake localities with increasing distance from the Petchenga-Nikel smelters have been investigated, including Kuetsjarvi and Rajakoski in Russia, Lake Inari in Finland, and Skrukkebukta and Vaggatem in Norway, as well as a reference lake locality (Stuorajavri) in the Kautokeino-Alta watercourse, Norway (Table 1 and Fig. 1). The analyses include fish community structure, population ecology, food web composition, heavy metal contaminations, and fish pathology. The fish studies have been carried out in close cooperation between Norwegian College of Fishery Science, University of Tromsø and Institute of North Industrial Ecology Problems, Kola Science Centre.

Table 1: Study localities sampled in the Inari-Paz watercourse during the project period from 2003 to 2005.

	Locality	Coun-try	Approx. distance from smelters	2003	2004		2005	
				Sept.	Aug.	Sept.	June	Sept.
1	Kuetsjarvi	R	5 km		X			
2	Skrukkebukta	N	16 km	X		X		X
3	Vaggatem	N	40 km	X		X		X
4	Rajakoski	R	65 km		X			
5	Lake Inari	F	100 km		X			
6	Stuorajavri[1]	N	290 km				X[2]	

[1] Reference lake located in the Kautokeino-Alta watercourse, Norway.

[2] Additional samples from August and September 2005 have been included in the fish ecology analyses.
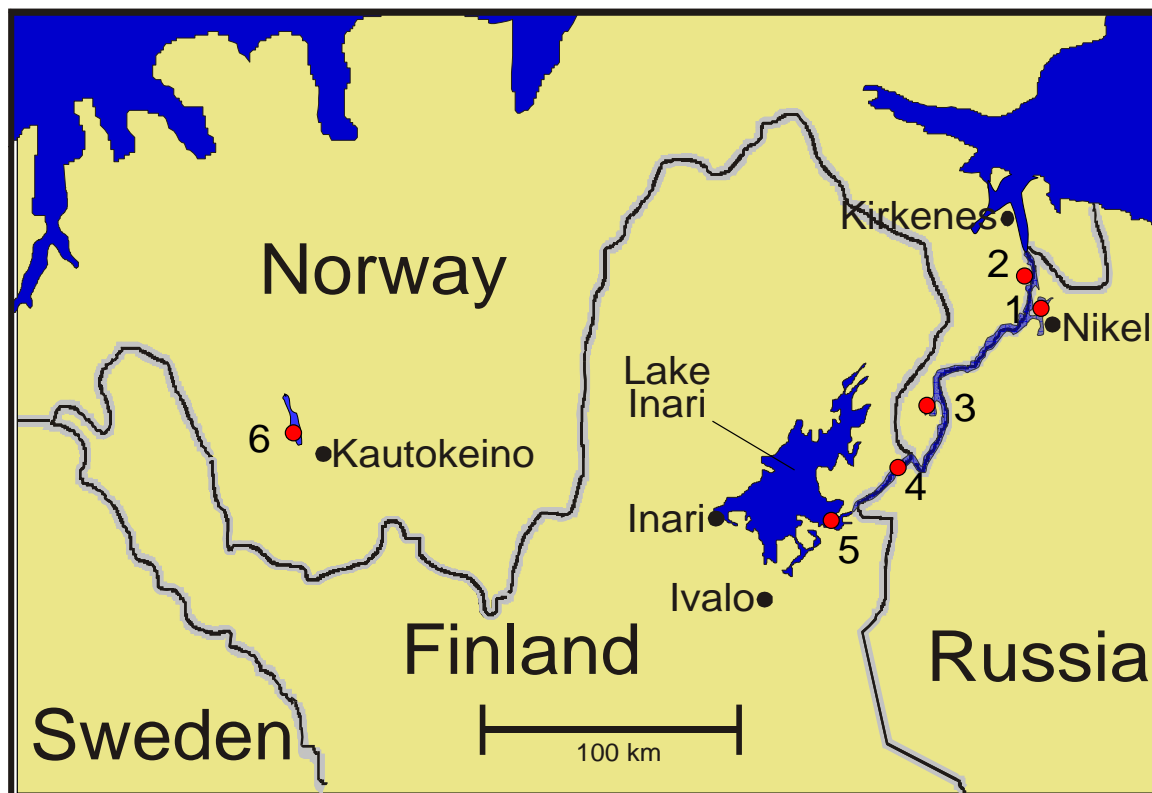

Fig. 1: Map of the study area with the six lake localities indicated in red. 1) Kuetsjarvi, 2) Skrukkebukta, 3) Vaggatem, 4) Rajakoski, 5) Lake Inari and 6) Stuorajavri.

2. Study area

The Inari-Paz watercourse drains north-east into the Arctic Ocean (Fig. 1), and is one of the larger watersheds in Fennoscandia with its 380 km maximum river length and mean flow of 175 $m^3 s^{-1}$ at the outlet. The catchment area is 18404 km^2 of which approximately 70 % belongs to Finland, 25 % to Russia and 5 % to Norway. Lake Inari (118 m above seal level) is the central lake locality in the watercourse, covering a total area of 1102 km^2. It is a relatively deep, oligotrophic lake that has been regulated since the 1940's with a regulation amplitude usually around 1.5 m. The sampling locality used in the present study in Lake Inari is located close to Nellim (68° 50' N, 28° 15' E). From the outlet in Lake Inari the watercourse runs along the national border between Norway and Russia before it enters the Arctic Ocean. The Norwegian-Russian part has a total area of 142 km^2, located in a quite narrow zone around their borderline. There are altogether seven water impoundments (hydropower reservoirs) in this part of the watercourse and rapids and waterfalls have disappeared, and the former river system is now dominated by a number of consecutive lakes and reservoirs. The water level fluctuations are small and usually less than 80 cm. The lake localities Rajakoski (69° 01' N, 28° 55' E; 90 m above sea level), Vaggatem (69° 13' N, 29° 14' E; 52 m a.s.l.) and Skrukkebukta (69° 33' N, 30° 7' E; 21 m a.s.l.) are located along the main stem of the Paz watercourse, whereas Kuetsjarvi (69° 27' N, 30° 07' E; 22 m a.s.l.) is located close by in a side-branch connected to the main watercourse at Salmijarvi. The reference lake Stuorajavri (69° 08' N, 22° 47' E; 374 m a.s.l.) is located in the Alta-Kautokeino watercourse, a few hundred km west of the Inari-Paz watercourse. All lakes are oligotrophic with some humic impacts. The geology in the Paz region is dominated by bedrock, mainly containing gneiss, and the watercourse is surrounded by a birch- and pinewood landscape with stretches of boggy land. The ice-free season both in Lake Inari and in lakes and reservoirs of the lower parts of the Paz watercourse, lasts from May/June to October/November.

3. Methods

3.1. Fish sampling and analyses

Fish sampling was carried out in the time period from 2003 to 2005. In Skrukkebukta and Vaggatem, sampling was carried out each year to explore annual variations in heavy metal contaminations, whereas in the other localities the sampling was carried out within a single year (see Table 1). Some additional heavy metal samples collected from fish in Skrukkebukta, Vaggatem and Rajakoski in 2002 have also been included. Fish sampling was performed both in the littoral (<8 m), profundal (>10 m) and pelagic habitats (0-6 m) using gillnets. The gillnets were 40 m long containing eight sections of 5 m with different mesh sizes. In the pelagic zone, 6 m deep floating nets were used, whereas 1.5 m deep bottom nets were employed in the littoral and profundal zones. The mesh sizes used were 10, 12.5, 15, 18.5, 22, 26, 35 and 45 mm (knot to knot). Additional samples of perch, pike and brown trout were collected using large-sized gillnets ($\geq$35 mm mesh size), and some samples (particularly brown trout) were also retrieved from the catches of local fishermen.

The fish were identified to species. In all studied lakes, the whitefish is represented by two different morphs, differentiated by their number and morphology of gill rakers and referred to as sparsely rakered (SR) and densely rakered (DR) whitefish. The SR whitefish have approx. 20-30 gill rakers that are short and widely spaced, whereas the DR whitefish have approx. 30-40 rakers that are longer and more densely packed (Amundsen et al. 2004a).

The two morphs were classified in the field from a visual evaluation of their gill raker morphology (see Fig. 2). The two whitefish morphs exhibit distinct genetic and ecological differences (Amundsen 1988, Amundsen et al. 2004a,b, Østbye et al. 2006), and are treated as functional species in the analysis and presentation of the results.

Each fish was measured for fork length and weight, sex and stage of maturation were recorded, and stomachs samples were collected and preserved in 96 % ethanol for diet analyses. Otoliths were sampled from whitefish and vendace and opercula from perch for age determinations. Tissue samples were furthermore collected from muscle, liver, gills, kidney and skeleton for analyses of heavy metal contaminations. Dissection of fish and sampling of tissues were carried out with knife, scissors and scalpel made of stainless steel. The tissue samples (weight 3-10 g) were put into plastic sachets and frozen.

In total more than 7.000 fish have been sampled from the six lake localities during the three year study period, but for practical reasons only sub-sets of fish have been included in the specific analyses. In summary, 3.872 fish have been aged, 4.627 fish stomachs have been included in the diet analyses and a total of 1650 tissue samples from 512 fish have been analysed for heavy metals.
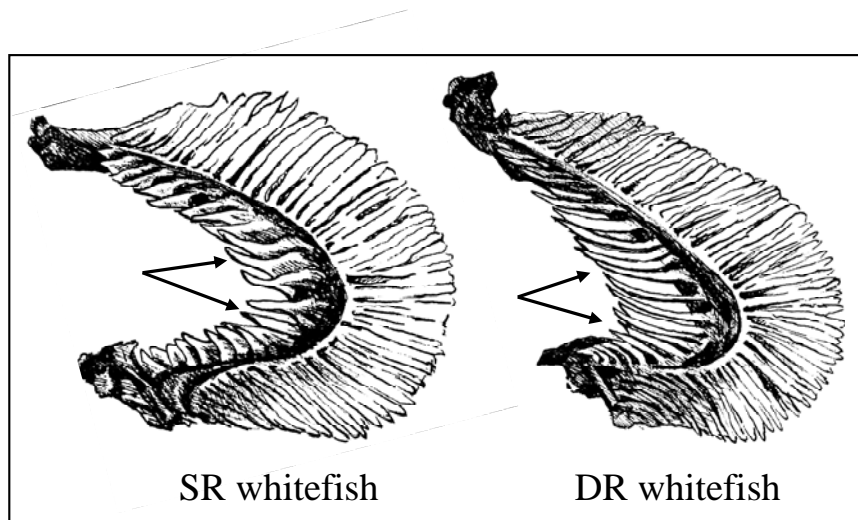

Fig. 2: Illustration of typical differences in gill morphology between the sparsely (SR) and densely rakered (DR) whitefish morphs. Arrows point to the gill rakers.

3.2. Ecological analyses of fish

Age determinations of whitefish and vendace was carried out by surface reading otoliths submerged in glycerol using a stereo microscope with 10-40X magnification and counting the hyaline zones. For perch, the opercula were cleaned for skin tissue and photographed with a digital camera. The age was thereafter determined from counting the hyaline zones on the operculum using the digitalized images.

The somatic growth rate of the fish (SR and DR whitefish, vendace and perch) was modelled using the simplified von Bertalanffy growth model (Bagenal 1978, Roff 1984):

$$L(t) = L_\infty(1-e^{-Kt})\qquad\qquad\qquad(1)$$

where $L(t)$ is the mean fish length at age t, L_∞ is the asymptotic length when age is close to infinity and K (Brody's growth coefficient) defines the rate at which the growth curve approaches the asymptote. L_∞ and K were estimated by non-linear regression.

To explore the size and age at maturation of SR and DR whitefish, vendace and perch, we used logistic regression with mature and immature fish as the nominal category variables to estimate the size at which 50% of the fish were sexually mature. As no major differences were found between the sexes, the presented results relate to the total fish populations.

For the dietary analyses of fish (mainly including SR and DR whitefish, vendace, perch, pike and brown trout), the prey items in the stomachs were identified and their relative contribution to the total diet estimated. The proportion of each prey category is expressed in percent of the total prey abundance (see Amundsen et al. 1996 for details). The diet composition estimates are presented for different size groups of the different fish species when sufficient materials are available.

The ecological analyses of fish do not include Rajakoski as the Norwegian part of the research team was not granted field work access to this locality by the military authorities.

3.3. Heavy metal analyses

The heavy metal analyses of fish muscle were conducted in the analytical laboratory of INEP and included cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), mercury (Hg), manganese (Mn), nickel (Ni), lead (Pb), strontium (Sr) and zinc (Zn). Some other elements were also determined, including potassium (K), sodium (Na), calcium (Ca) and magnesium (Mg). The heavy metal samples were dried to constant weight at $90^{o}C$. Then samples were digested in mixture of nitric acid (4ml), hydrochloric acid (0.5ml) and water (2 ml) in Microwave digestion system (Multiwave 3000, Anton Paar, AUSTRIA) using a digestion protocol of two stages: 13 min at 600wt and 10 min at 400wt (according to manufacturer specifications). After cooling, the solution was diluted to 15 ml with de-ionized water.

The contents of Cu, Ni, Al, Mn and Sr in muscle, liver and kidney were determined by atomic absorption spectroscopy (AAS) (Perkin Elmer Model 5000, graphite-furnace HGA-400). Cd and Pb were analyzed by graphite-furnace (Perkin Elmer Model AAnalyst -800 with Zeeman – effect background correction and automatic sampler). $NH_4H_2PO_4$ and $Mg(NO_3)_2$ were used as Matrix Modifier. Fe, Zn and Mn, Sr in gills and skeleton were analyzed by flame AAS (AAS-30, Carl Zeiss Jena), Ca and Mg by flame atomic absorption, and K and Na by emission spectrometry in flame (Perkin Elmer Model 360). Hg was determined with mercury analysis system FIMS-100 (Perkin Elmer) operated according to manufacturer specifications. SnCl was used as reducing agent.

The concentrations of heavy metals in fish are expressed as µg/g dry weight of tissue, and for Ca, Mg, K, Na as mg/g dry weight. The detection limits were 0.01 µg/g for Cd, 0.05 for Pb, 0.005 for Hg, 0.02 for Cu, 0.05 for Ni. Working standard solutions for each element were prepared from certified standard solution (1mg/ml) Fluka Chemie GmbH, Switzerland. A quality assurance program has been carried out, consisting of analyses of the standard reference material DORM-2 (dogfish muscle). The outcome of these analyses is presented in Table 2.

Table 2: Results of quality assurance analyses of the standard reference material DORM-2 (dogfish muscle).

	Cu	Ni	Cd	Pb	Mn	Zn	Al	Fe	Hg
Certified values	2.34 ±0.16	19.4 ±3.1	0.043 ±0.008	0.065 ±0.007	3.66 ±0.34	25.6 ±2.3	10.9 ±1.7	142 ±10	4.64 ±0.26
D1	2.21	16.9	0.033	0.061	3.50	22.2	10.6	140	4.39
D2	1.63	14.0	0.033	0.057	2.74	22.7	11.6	128	4.46
D3	2.22	18.0	0.036	0.035	3.72	22.2	8.4	141	4.69
D4	1.95	17.9	0.040	0.064	3.40	22.4	10.6	126	4.45
D5	2.25	17.8	0.035	0.060	3.73	23.4	10.5	133	4.71
D6	2.26	17.8	0.035	0.059	3.38	23.6	10.6	136	4.58
D7	3.21	18.9	0.034	0.116	3.60	23.8	9.48	133	4.66
Mean	2,25	17,3	0,035	0,065	3,44	22,9	10.3	134	4,56
S.E.	0.18	0.60	0.001	0.009	0.13	0.3	0.4	2	0.05

Statistical handling of the heavy metal data from fish

Possible relationships between heavy metal contents and fish length were examined by ANOVA (log-transformed data; Bonferroni adjustments for multiple comparisons) using lake locality as a covariate. Significant variations in heavy metal contents with increasing fish size were observed in less than 25% of the performed tests (198 in total), and no consistent patterns were observed with respect to specific metals or fish species. Fish size has therefore not been taken into further consideration in the analysis and presentation of the heavy metal data. Spatial, temporal and between-species differences in heavy metal contents have been tested statistically using Kruskal-Wallis test or Mann-Whitney U-test. The Bonferroni adjustment has routinely been employed for multiple comparisons.

3.4. Pathological analyses

The conducted pathology-morphological studies, including clinical research of fish and post-mortem examinations, have earlier been applied in a series of other studies (Arshanitsa & Lesnikov 1987, Moiseenko at al. 1995, Moiseenko 1997, Kashulin et al. 1999). Many fish species acquire pathologies of variable degrees (especially within salmonid and whitefish families) after poisonous action of different materials (Kashulin et al. 1999). Species within the whitefish and salmonid families are highly suitable for pathologic studies on account of their sensitivity to environmental conditions, wide-spread occurrence and ecological flexibility. The performance of pathological studies under field conditions allows

highly informative data to be collected in order to detect disorders in vitally important organs of fish.

The following pathologies of fish organs and tissues were diagnosed:

- outward appearance (depigmentation of skin, depigmentation of scull);
- spine (curvatures – scoliosis, kyphosis, lordosis);
- gills (warped, split and clavate rakers, irregular row and partial absence of rakers, necrotic disorders of gills (anaemic ring));
- muscular tissue of pikes (changes of color and green shade);
- gonads (anisochronous and asymmetric maturation, strangulated and twisted gonads)
- liver (degeneration of tissue, hyperemia, focal necrosis resulting in changes of color and stretching);
- kidney (hyperemia, hemorrhages, necrosis focuses, dystrophic changes of epithelium of tubules and granulation). The most frequent disease of kidneys – connective-tissue expansions in the shape of white bands in the tail.

Tissue samples for histopathological analysis were removed from each fish the following order: gill, liver, spleen, and kidney. After removal, the gonads and liver were weighed (to nearest 0.1g). All tissues for histopathology were fixed in Bouin solution. Two sections of the gills (first and second right-side gill arches), and the middle and caudal thirds of the kidneys were collected. Livers were apportioned for biochemical and histopathological analysis. Paraffin blocks were sectioned at 5-7 µm, mounted on glass slides, and then stained with haematoxylin & eosin. All tissue sections were screened and subjected to detailed histopathological analysis. Sections were prepared according to standard methods (Ham and Corwack 1979).

Fish sampling

4. Results

4.1. Fish community composition

In total, thirteen fish species were recorded in the studied lakes, including the two whitefish morphs (Table 3). Most of these species are native in their respective localities, but vendace and lake charr have been introduced to Lake Inari and have invaded the lower part of the Inari-Paz watercourse. A few more fish species have been introduced to Lake Inari, including Atlantic salmon from the freshwater resident Lake Saima population, but these were not observed during the present survey. Whitefish was the dominant fish species in all lakes and was usually prevalent in all the main lake habitats (Fig. 3). The SR whitefish dominated in the littoral and profundal habitats, whereas the DR whitefish was most common in the pelagic zone. However, in Kuetsjarvi a quite contrasting pattern was observed, with small-sized DR whitefish dominating in the littoral zone and the main bulk of SR whitefish apparently being relegated to the profundal. The introduced vendace was recorded in all lake localities in the Inari-Paz watercourse and dominated in the pelagic habitat in Skrukkebukta, Vaggatem and Lake Inari. In Kuetsjarvi, in contrast, the densely rakered whitefish morph was still the dominant pelagic species. Perch was an important species in the littoral zone of all lakes and was also quite frequently recorded in the profundal of Skrukkebukta and Vaggatem. Among the less commonly recorded species, pike was mostly found in the littoral zone and occasionally in the pelagic, whereas burbot was found in the profundal and littoral habitats.

Table 3: List of fish species recorded in the studied lakes (Ku – Kuetsjarvi, Sk – Skrukkebukta, Va – Vaggatem, In – Lake Inari, St – Stuorajavri). n = native species and i = introduced species.

Fish species	Ku	Sk	Va	In	St
SR whitefish (*Coregonus lavaretus*)	n	n	n	n	n
DR whitefish (*Coregonus lavaretus*)	n	n	n	n	n
Vendace (*Coregonus albula*)	i	i	i	i	
Perch (*Perca fluviatilis*)	n	n	n	n	n
Pike (*Esox lucius*)	n	n	n	n	n
Burbot (*Lota lota*)	n	n	n	n	n
Brown trout (*Salmo trutta*)	n	n	n	n	n
Grayling (*Thymallus thymallus*)	n	n	n	n	
9-sp. stickleback (*Pungitius pungitius*)	n	n	n	n	
3-sp. stickleback (*Gasterosteus aculeatus*)				n	
Minnow (*Phoxinus phoxinus*)	n	n	n	n	n
Arctic charr (*Salvelinus alpinus*)				n	n
Lake charr (*Salvelinus namaycush*)				i	

Brown trout and Arctic charr were caught in all three habitats, but most commonly in the littoral and pelagic, whereas grayling, nine-spined sticklebacks and minnows are known mainly to occur in the littoral zone. Fig. 4 summarizes the typical habitat distribution of the most common fish species in the studied lakes.
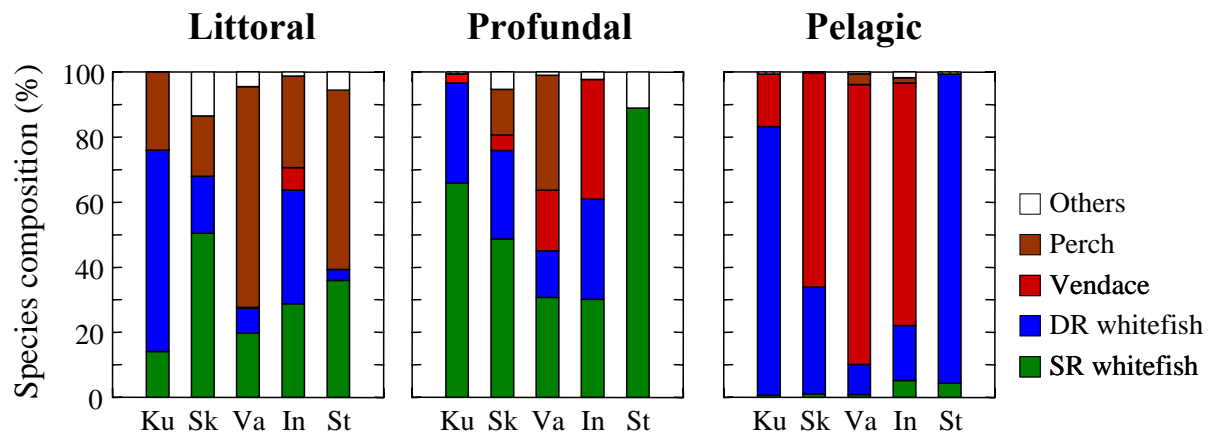

Fig. 3: Fish community composition in the littoral, profundal and pelagic habitats of the studied lakes (Ku – Kuetsjarvi, Sk – Skrukkebukta, Va – Vaggatem, In – Lake Inari, and St – Stuorajavri).
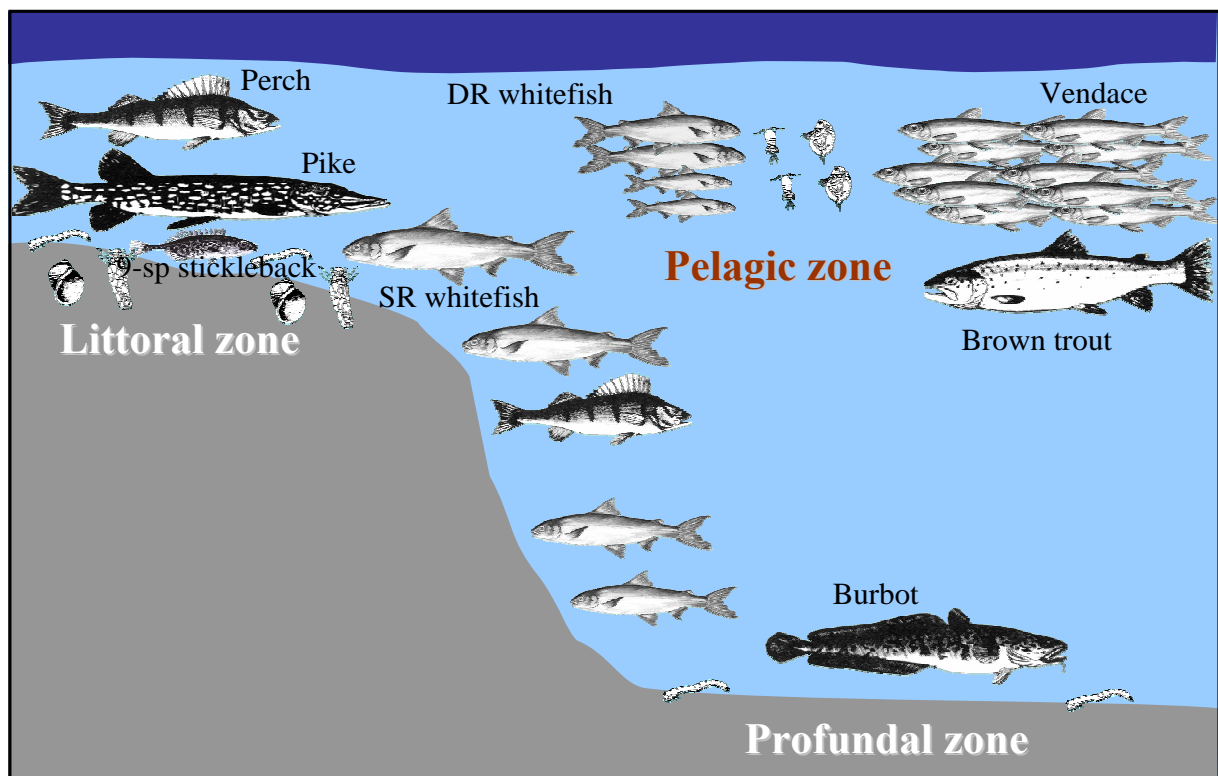
Fig. 4: Typical habitat distribution of the most common fish species in the studied lakes in the Inari-Paz watercourse.

4.2. Fish population ecology

The population ecology studies were restricted to the most numerously occurring fish species and include the two whitefish morphs, vendace and perch.

a) Size and age distribution
The DR whitefish populations were dominated by small-sized fish in all lake localities in the Inari-Paz watercourse (Fig. 5), with the median lengths ranging from 10.5 cm in Kuetsjarvi to 12.0 cm in Lake Inari. In the reference lake Stuorajavri, the DR whitefish population in contrast mainly consisted of fish >15 cm and with a median length >20 cm. A similar pattern was also observed for the SR whitefish, where large-sized fish dominated the population in Stuorajavri. The smallest SR whitefish were recorded in Kuetsjarvi (median length 13.5 cm), increasing through Skrukkebukta (15.2 cm) to a maximum in Vaggatem (22.8 cm) and being somewhat smaller again in Lake Inari (18.4 cm). In all lakes, the DR whitefish populations consisted of significantly smaller fish than the SR whitefish. Also the vendace populations were dominated by small-sized fish, in particular in Vaggatem where the median size was only 9.4 cm. In Kuetsjarvi and Skrukkebukta the median sizes of vendace were 11.1 cm and 12.7 cm, respectively, whereas the fish caught in Lake Inari were somewhat larger (median length 14.6 cm). The perch populations exhibited a more similar size distribution with median lengths ranging from 15.5 to 18.8 cm, with the largest fish being caught in Vaggatem (Fig. 5).

The age distributions of fish from the Inari-Paz watercourse localities were dominated by young fish mainly ≤5 years (Fig. 6). In Stuorajavri in contrast, only a few young fish were caught and most fish were older than 10 years. A similar pattern was also observed for the SR whitefish with most fish being older than 8 years in Stuorajavri and younger than 7 years in the localities in the Inari-Paz watercourse. Among the vendace populations, the age distributions were almost completely restricted to fish ≤4 years. The perch populations in contrast consisted of a wider age range with the oldest fish being recorded in Vaggatem.

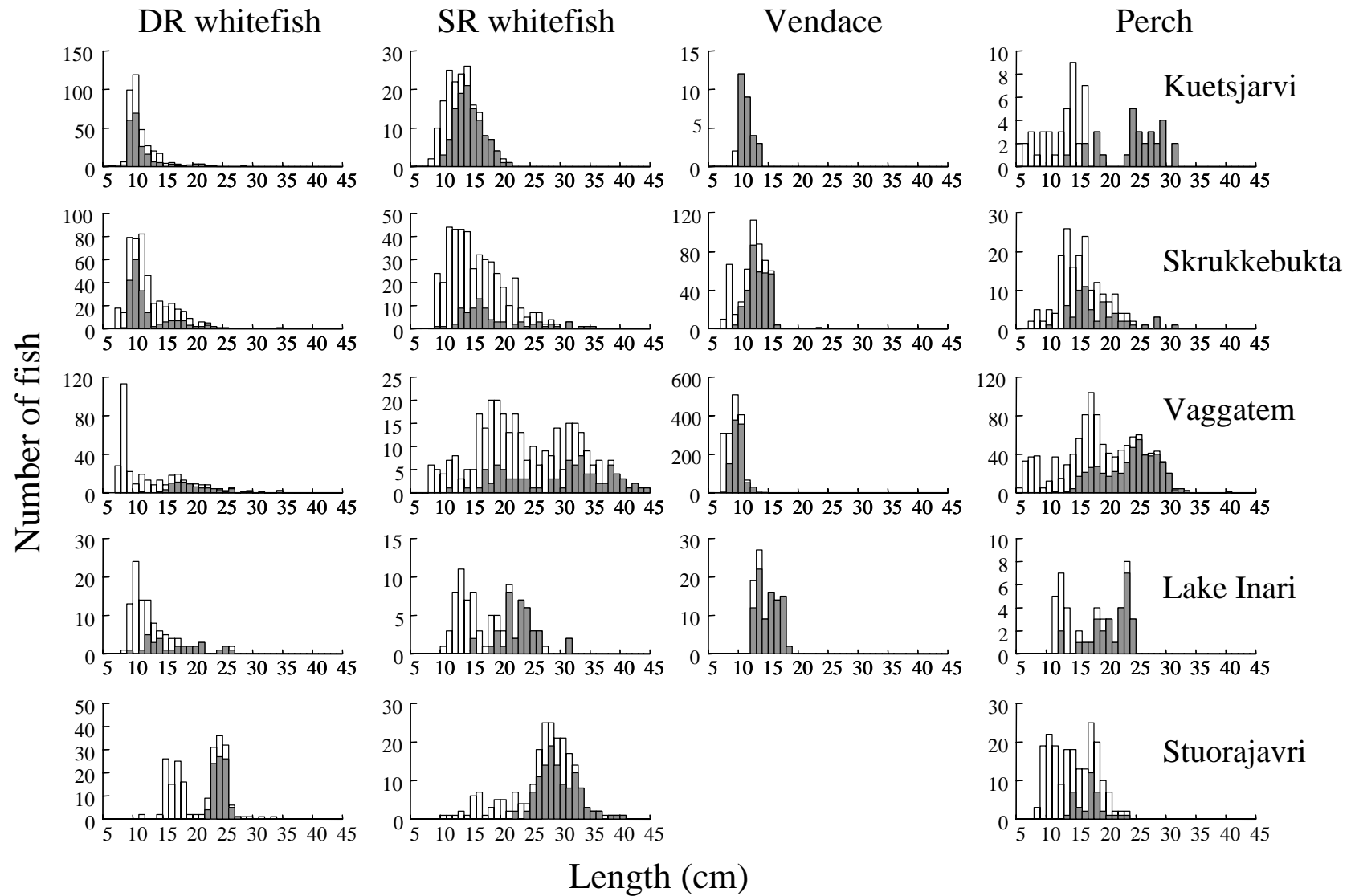*Common fish species in the Inari-Paz watercourse*

Fig. 5: Size distribution of DR and SR whitefish, vendace and perch in the studied lakes. Shaded bars represent sexually mature fish.
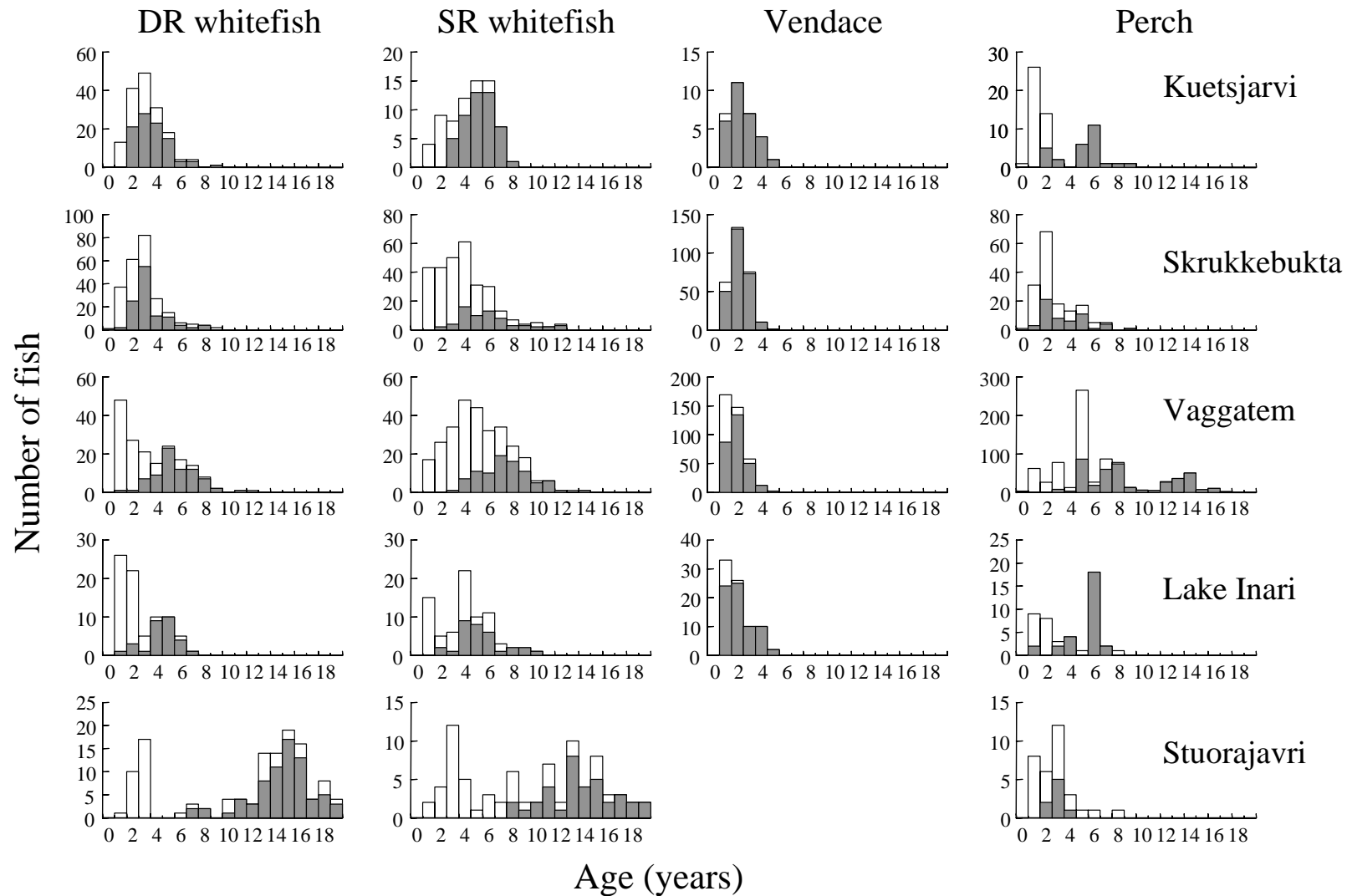
Fig. 6: Age composition of DR and SR whitefish, vendace and perch in the studied lakes. Shaded bars represent sexually mature fish.

b) Growth

Among the DR whitefish populations, the slowest somatic growth rate was observed in Kuetsjarvi (Fig. 7a) with a L_∞-value of only 16.9 cm (Table 3). In the other lakes the DR whitefish grew significantly faster with the highest growth rates observed in Vaggatem and Stuorajavri. In most lakes the SR whitefish grew faster than the DR whitefish (Fig. 7b). The slowest growth rate of SR whitefish was also observed in the Kuetsjarvi population with a L_∞-value of 15.4 cm which was even lower than observed for for the DR whitefish in this lake. The growth rates of the SR whitefish were considerably higher in the other lakes, and particularly in Vaggatem. Vendace exhibited modest growth rates in all lakes, with the slowest growth occurring in Vaggatem and Kuetsjarvi and the fastest in Lake Inari (Fig. 7c). For perch, in contrast, the highest growth rate was observed in Kuetsjarvi and the lowest in Skrukkebukta, but the overall differences between the lakes were moderate (Fig. 7d).
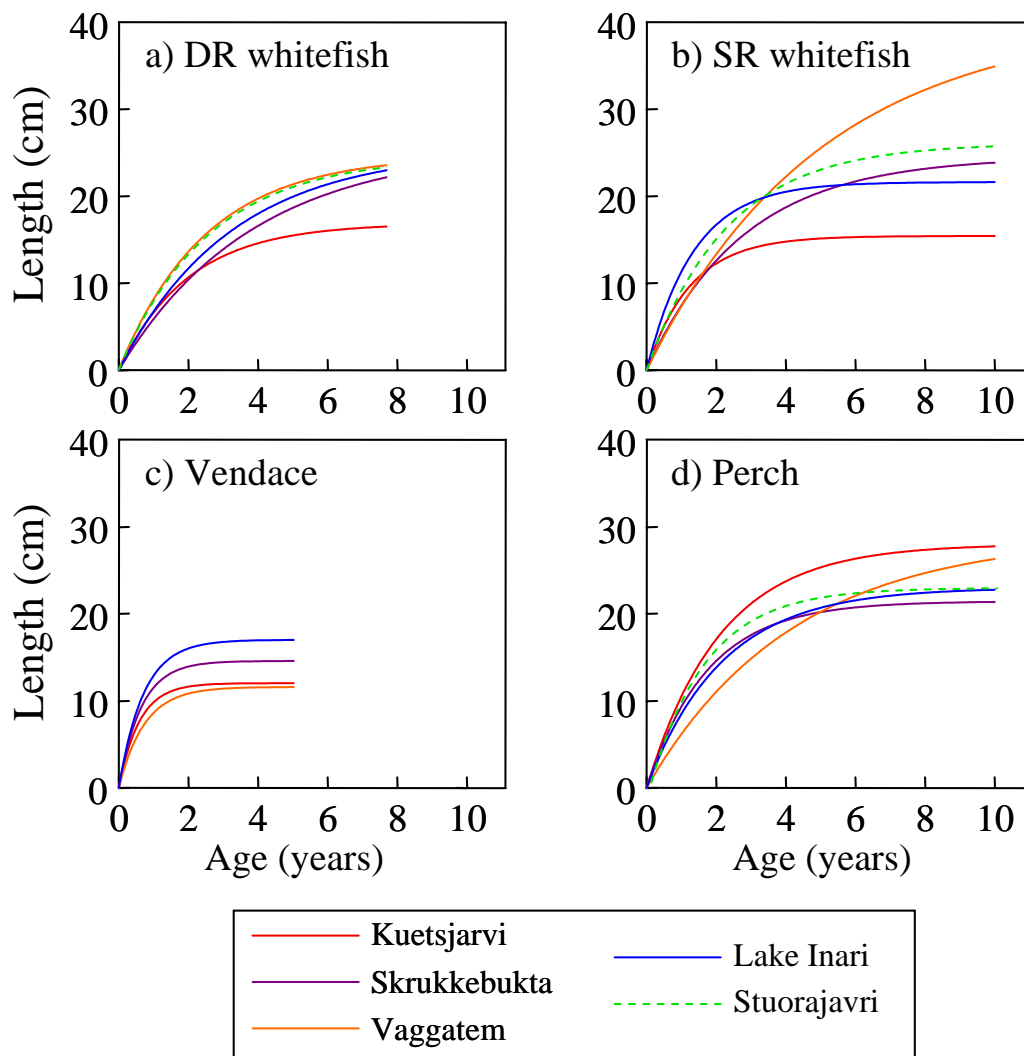
Fig. 7: Growth rates of a) DR whitefish, b) SR whitefish, c) vendace and d) perch in the studied lake localities. Estimates are based on the von Bertalanffy growth model (see Table 3 for a presentation of the estimated model parameters).

Table 3: Growth parameters estimated from the von Bertalanffy growth model (L_∞ = asymptotic length, K = Brody's growth coefficient, s.e. = standard error).

Species	Lake	L_∞	s.e.	K	s.e.	R^2
DR whitefish	Kuetsjarvi	16,9	1,98	0,50	0,18	0,88
	Skrukkebukta	23,6	3,37	0,26	0,08	0,91
	Vaggatem	24,2	1,43	0,40	0,07	0,97
	Lake Inari	25,3	7,70	0,31	0,19	0,86
	Stuorajavri	24,5	1,92	0,39	0,09	0,92
SR whitefish	Kuetsjarvi	15,4	0,71	0,79	0,17	0,94
	Skrukkebukta	24,5	1,93	0,36	0,08	0,93
	Vaggatem	40,4	3,39	0,21	0,04	0,97
	Lake Inari	21,6	0,80	0,74	0,14	0,99
	Stuorajavri	26,1	0,82	0,43	0,05	0,98
Vendace	Kuetsjarvi	12,0	0,70	1,70	0,22	0,97
	Skrukkebukta	14,6	1,01	1,56	0,23	0,98
	Vaggatem	11,6	0,51	1,36	0,17	0,96
	Lake Inari	17,9	0,68	1,42	0,15	0,98
Perch	Kuetsjarvi	28,0	0,70	0,47	0,03	0,99
	Skrukkebukta	21,5	1,28	0,57	0,10	0,98
	Vaggatem	28,9	1,44	0,24	0,03	0,99
	Lake Inari	23,0	1,47	0,46	0,09	0,95
	Stuorajavri	22,5	0,45	0,61	0,05	0,99

c) Sexual maturation

For DR whitefish, the size at 50% maturation was lowest in Kuetsjarvi (9.0 cm) and Skrukkebukta (9.4 cm), with intermediate levels observed in Vaggatem (17.0 cm) and Lake Inari (15.5 cm) and highest in Stuorajavri (21.4 cm) (Fig. 8a). Also for the SR whitefish the smallest size at maturation occurred in Kuetsjarvi (11.2 cm), compared to considerably larger sizes in Skrukkebukta (28.7 cm) and Vaggatem (31.4 cm) and intermediate sizes in Lake Inari (19.0 cm) and Stuorajavri (24.5 cm). Less variation was observed in size at maturation of perch which ranged from ca. 16-19 cm (Fig. 8a).

Also the age at 50 % maturation of the DR and SR whitefish was lowest in Kuetsjarvi (2.4 and 3.4 yr, respectively) and generally increased along the gradient of lakes towards a maximum age in Stuorajavri (8.5 and 10.3 yr, respectively) (Fig. 8b). Similarly, the age at maturation of perch was lowest in Kuetsjarvi (2.5 yr), but only slightly higher in Lake Inari (3.1 yr) and highest in Vaggatem (5.6 yr). The age data of perch from Stuorajavri were not sufficient to produce a logistic regression estimate of the age at maturation.

For vendace, most of the sampled fish were sexually mature in all lakes, and even among 1-yr old fish the majority of the individuals had matured (Fig. 6). The smallest mature vendace caught were furthermore around 8 cm (Fig. 5), i.e. close to the minimum size of vendace in the samples. It was therefore not possible to explore any lake differences in maturation size or age of vendace by logistic regression.
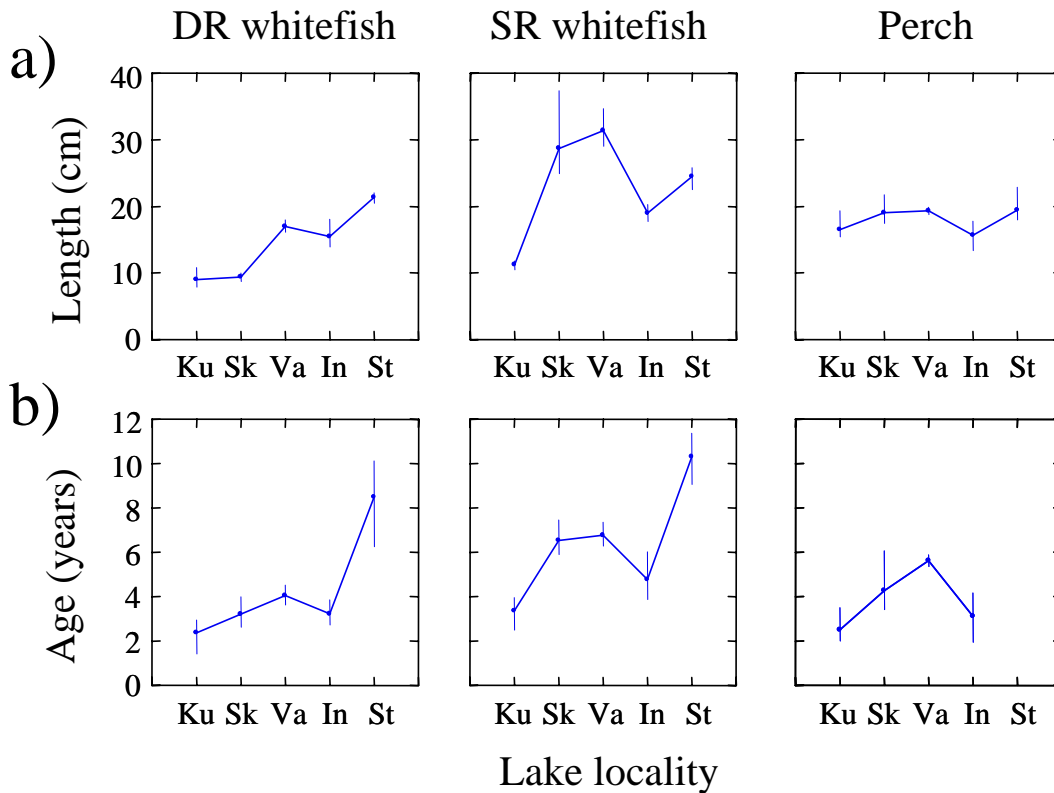

Fig. 8: Mean size (a) and age (b) at first reproduction (i.e. length and age with 50 % mature individuals) of DR whitefish, SR whitefish and perch in the studied localities estimated by logistic regression (with 95% confidence limits). (Ku – Kuetsjarvi, Sk – Skrukkebukta, Va – Vaggatem, In – Lake Inari, and St – Stuorajavri)

4.3. Feeding ecology and food web structure

a) Coregonid diet

 The coregonids (SR whitefish, DR whitefish and vendace) fed on a variety of invertebrates, including zooplankton, zoobenthos and surface insects in their diets (Fig. 9). There were, however, some distinct differences between the species and to some extent also between the lakes. Characteristic dietary changes were also observed with increasing size of the fish reflecting ontogenetic diet shifts, particularly within the whitefish morphs. The SR whitefish were in all lakes feeding mainly on benthic invertebrates like insect larvae, molluscs and benthic crustaceans, but the smallest size groups of fish were in some lakes feeding on zooplankton (Fig. 9a). This pattern of ontogenetic diet shift was particularly clear cut in Stuorajavri, where fish <20cm were almost exclusively feeding on pelagic cladocerans (mainly *Daphnia* and *Bosmina*), whereas fish >20 cm predominantly consumed benthic invertebrates. Also the DR whitefish changed from a dominance of zooplankton in the smaller size groups to zoobenthos among larger fish (Fig. 9b). However, since smaller-sized fish

generally dominated the DR whitefish populations in lakes in the Inari-Paz watercourse, zooplankton constituted the main part of the diet of this morph. The dietary dominance of zooplankton was most pronounced in DR whitefish in Stuorajavri. In Vaggatem, in contrast, neither the DR nor the SR whitefish utilised zooplankton to any extent. This may be related to the strong dominance of vendace in the pelagic zone of this lake (conf. Fig. 2). Vendace is a specialised zooplankton predator, and crustacean zooplankton (including both pelagic cladocerans and copepods) were the dominant prey of vendace in all lakes (Fig. 9c).

b) Piscivore diet

Perch, pike and brown trout were the dominant piscivorous species in the studied lakes. Perch were caught in a broad size range in all lakes, and appeared to exhibit several ontogenetic diet shifts throughout their life cycles (Fig. 10a). Zooplankton was only consumed by the smallest size groups. These smaller-sized fish groups were however mostly feeding on zoobenthos and surface insects, changing to a dominance of nine-spined sticklebacks in intermediate size groups, and to whitefish and other fish prey among the largest perch. Nine-spined sticklebacks were particularly important in the perch diet in Kuetsjarvi, but were also a common prey of the perch in the other localities in the Paz watercourse. The marked dominance of this prey in the Kuetsjarvi perch is likely related to the fact that the nine-spined sticklebacks in this lake were heavily infected by the large-sized tapeworm *Schistocephalus solidus*, which is known to result in a major increase in the predation vulnerability of sticklebacks. In Vaggatem, some large-sized perch were also found to be cannibalistic.

The pike and brown trout samples were restricted to large-sized fish, and for both species the observed diets exclusively consisted of fish prey (Fig. 10b,c). Pike had mainly consumed whitefish prey, whereas brown trout from the lakes in the Inari-Paz watercourse largely had been feeding on vendace and in Stuorajavri only on whitefish. In Vaggatem where vendace was by far the most common in the fish community of the pelagic zone, the brown trout diet was almost completely dominated by this species, whereas in Lake Inari and to some extent also in Skrukkebukta, the DR whitefish also gave a significant contribution to the trout diet.

The few burbots that were caught during the study had mainly consumed whitefish and nine-spined sticklebacks, whereas two lake charr sampled in Lake Inari had been feeding on whitefish.

c) Food web structure

Based on the diet information of the most important fish species in the studied lakes, the basic food web structure of lakes in the Inari-Paz watercourse have been summarized in Fig. 11. The food web has two basic compartments related to the pelagic and benthic food chains, respectively. Vendace is a specialized zooplankton feeder, and has become the principal zooplankton predator in the pelagic zone after it was introduced to the Inari-Paz watercourse. The DR whitefish, which also typically is a zooplankton predator as e.g. demonstrated from Stuorajavri, has in the Inari-Paz watercourse to a large extent been relegated from the pelagic, zooplanktivore niche by competition from vendace, and thus exhibited a highly mixed diet consisting of both zoobenthos and zooplankton. The SR whitefish is typically a zoobenthos predator residing in the littoral habit, but do also to a large extent utilize zooplankton in the first part of its life. Perch is the species that exhibit the most typical ontogenetic diet shifts, ranging from zooplankton to zoobenthos to small fish like 9-spined sticklebacks and later to large fish like whitefish during the course of its lifecycle. Large-sized perch is together with pike and burbot the typical fish predators in the benthic habitats, feeding mainly on 9-spined sticklebacks and whitefish in the littoral and profundal, whereas brown trout is the principal pelagic fish predator feeding on vendace and DR whitefish in the pelagic zone.
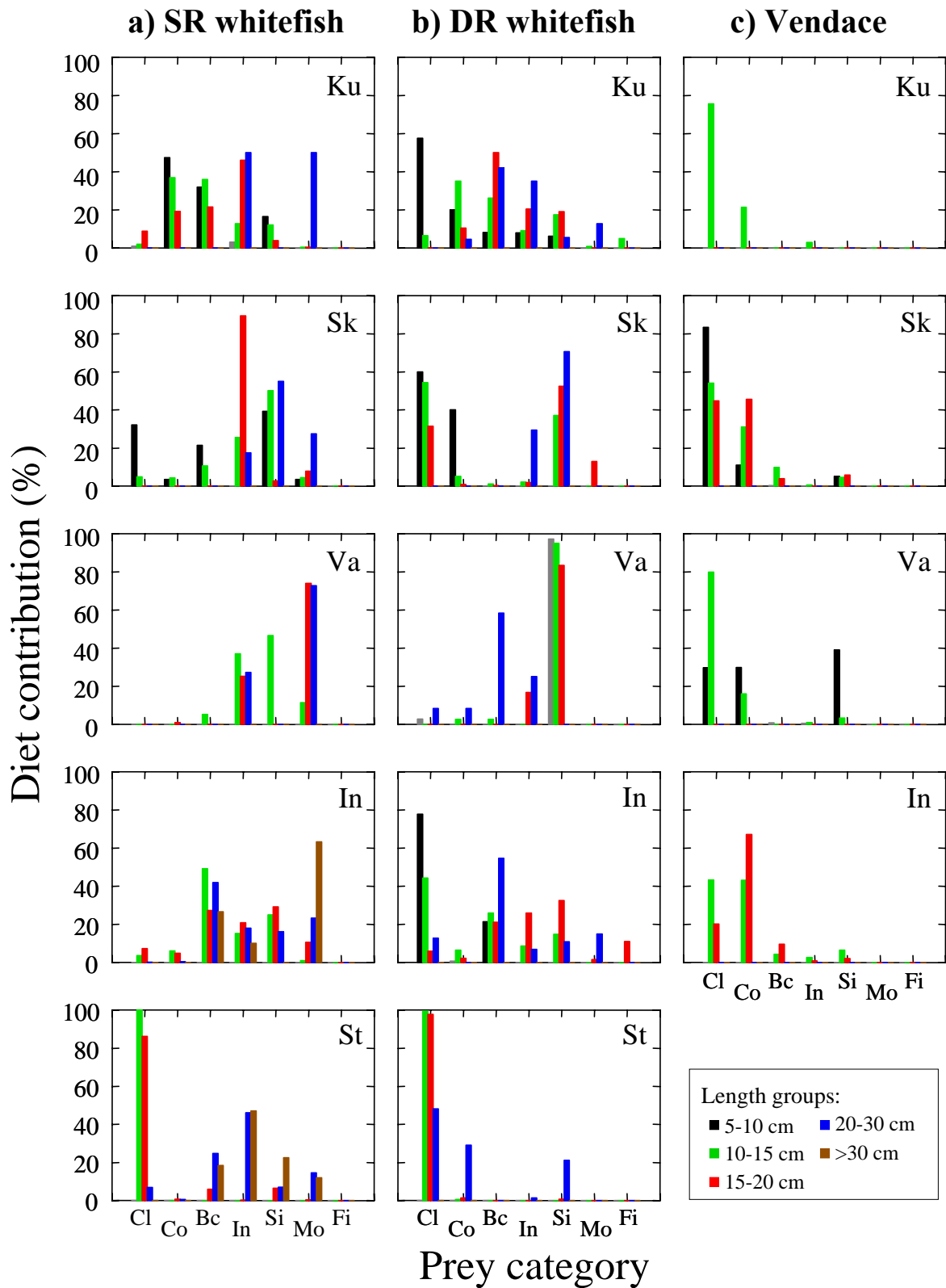
Fig. 9: Diet composition of a) SR whitefish, b) DR whitefish and c) vendace. The diet categories are: Cl – cladoceran zooplankton (mainly *Bosmina* and *Daphnia*), Co – copepod zooplankton (mainly *Cyclops* and *Eudiaptomus*), Bc – benthic crustaceans (mainly *Eurycercus* and *Gammarus*), In – insect larvae and pupae, Si – surface insects, Mo – molluscs and snails, Fi – fish eggs.
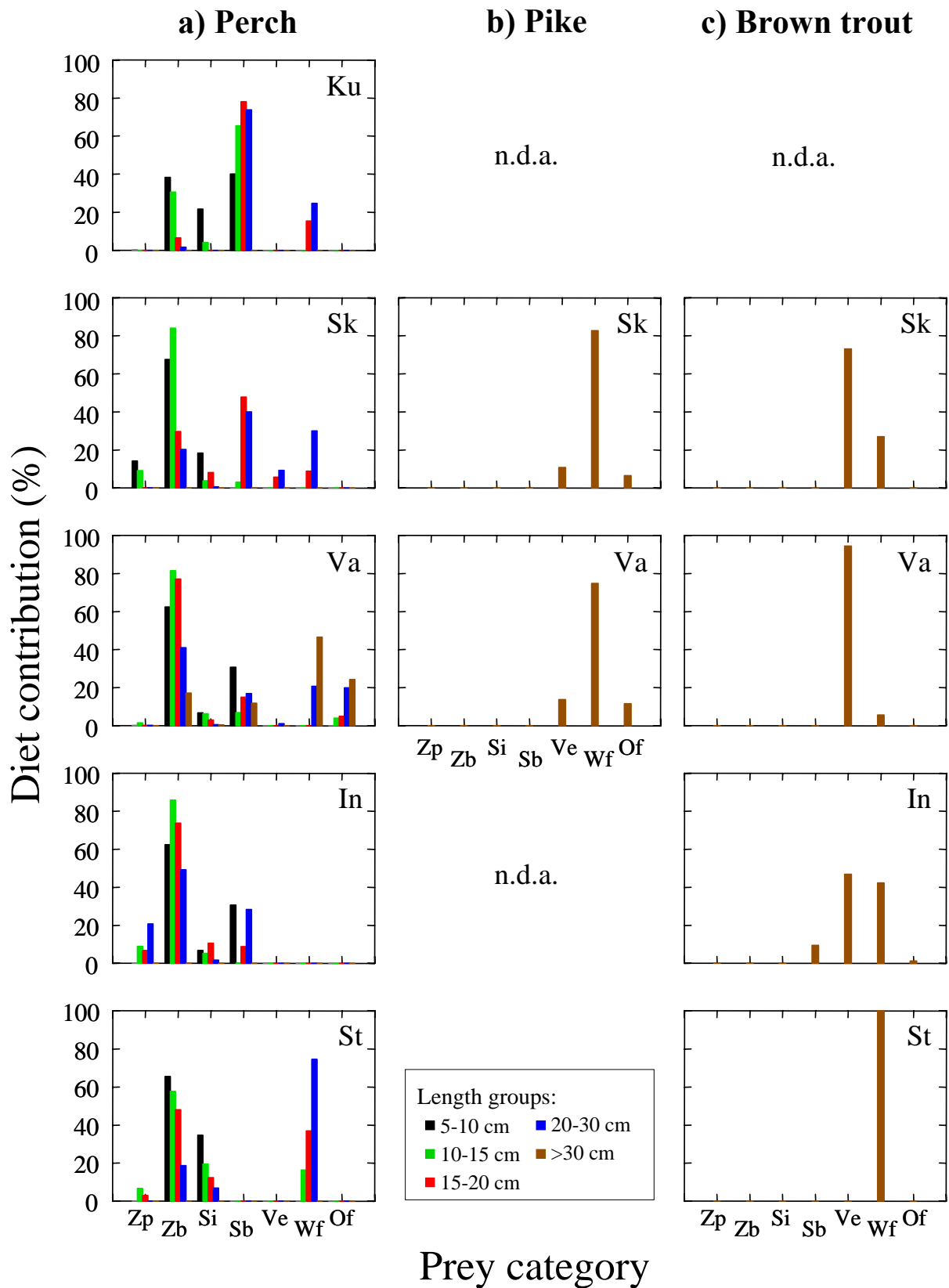
Fig. 10: Diet composition of a) perch, b) pike and c) brown trout. The diet categories are: Zp – zooplankton, Zb – zoobenthos, Si – surface insects, Sb – sticklebacks, Ve – vendace, Wf – whitefish, Of – other fish. (n.d.a. = no data available)
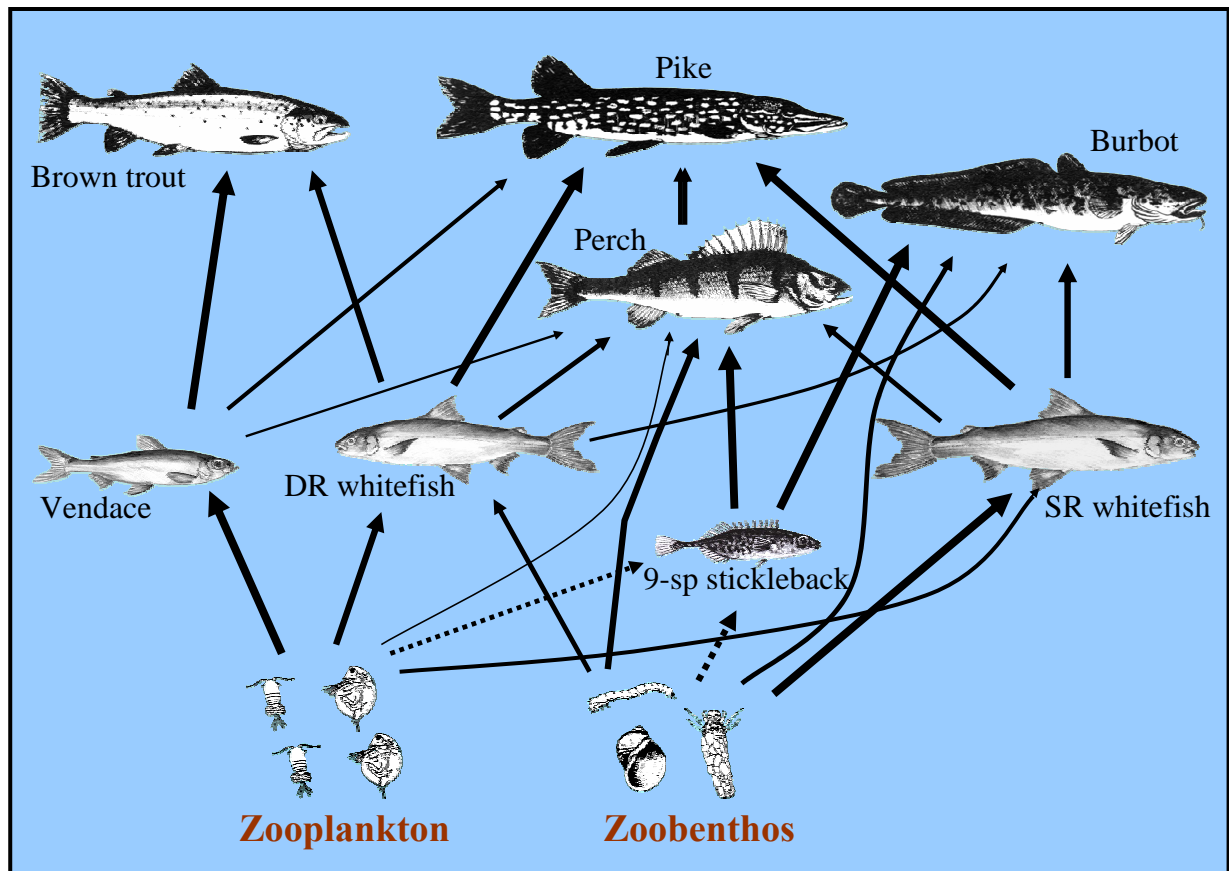
Fig. 11: Summary of the basic food web structure of the fish communities in the studied lake localities in the Inari-Paz watercourse (The line thickness indicates the assumed importance of the different links. Stippled lines represent unconfirmed links).

4.4. Heavy metal contaminations in fish

a) Spatial variations along the lake gradient

Heavy metal samples were collected from SR and DR whitefish, perch and pike in all six lake localities, facilitating a comparison of heavy metal contents along the lake gradient from Kuetsjarvi close to the Nikel smelters to the remote reference locality Stuorajavri. Three main patterns were observed for the concentrations of the different heavy metals in the fish organs, including:

i)   a decreasing trend in the metal contents with increasing distance to the smelters,

ii) an increasing trend in the metal contents with increasing distance to the smelters, and

iii) more variable fluctuations with no distinct trend.

The observed trends were generally most pronounced in SR and DR whitefish and less marked in perch and pike. Ni and Cd were the most characteristic examples of the pattern showing a decreasing metal concentration with increasing distance from the smelters (Fig. 12 and 13). For both metals there were distinct changes in the content levels over the spatial

gradient, particularly in SR and DR whitefish, with high metal concentrations in fish from Kuetsjarvi, decreasing sharply towards Skrukkebukta and Vaggatem and in general being low in the other localities. Similar, but less pronounced patterns could also be seen for Cu, Mn, Al and Sr (Appendix 1; fig. 1.1, 1.2, 1.3 and 1.4), and to some extent also for Pb (Appendix 1; fig. 1.5). The Hg contents in the fish tissues showed a totally opposite pattern (Fig. 14). The lowest levels were consistently seen in Kuetsjarvi, whereas the highest Hg levels mainly were observed in fish from Stuorajavri. Intermediate peaks in Hg contents were furthermore seen in fish from Skrukkebukta and Vaggatem. For Zn, no particular trends could be seen in metal concentration with increasing distance from the smelters (Appendix 1; fig. 1.6).

b) Species differences

A comparison of the contamination levels of heavy metals in the different fish species (SR and DR whitefish, vendace, perch, pike and brown trout) were restricted to Skrukkebukta and Vaggatem, as these were the only localities were all species were represented in the data set. The contamination levels did in general exhibit significant differences between the fish species, but few clear-cut patterns could be revealed (Appendix 1; fig. 1.7 and 1.8). Most noteworthy was a tendency for a higher content level of Ni and partly Cd in the coregonid species (SR and DR whitefish and vendace) compared to the piscivore species (perch, pike and brown trout). The Hg levels were furthermore in general highest in perch.

c) Annual variations

In Skrukkebukta and Vaggatem, fish were sampled for heavy metal analyses over the 3-yr project period to facilitate an exploration of annual variations in heavy metal contents. Only SR and DR whitefish and pike were included in these studies. A statistical test of the inter-annual variations showed that in 65% of the comparisons there were no significant differences (Kruskal-Wallis test; $p > 0.05$, 135 tests in total). Interestingly, however, for Hg a consistent and significant increase in the heavy metal contents was observed in 14 out of 15 comparisons ($p < 0.01$). For the other metals, significant differences were observed on a more occasional basis, but some important short-term changes were also recorded (Appendix 4, 5 and 6).

d) Long-term changes

The heavy metal concentrations observed in fish in the present study have been contrasted with the results of a heavy metal study carried out in 1991-1992 in Kuetsjarvi, Vaggatem and Bjørnevatn close to Skrukkebukta (see Amundsen et al. 1993, 1997). In most of the comparisons (77.5% out of 253 tests in total) there were no significant differences in the heavy metal concentrations between 1991-1992 and 2003-2005 (Mann-Whitney U-test, $p > 0.05$). For two metals, however, consistent and significant changes had occurred. Firstly, the Hg concentrations in muscle, liver and kidneys exhibited a significant decrease from 1991-1992 in DR and SR whitefish, perch and pike from Kuetsjarvi (Fig. 15). The observed changes in Hg levels were large, amounting to a mean reduction of 74% in the muscle tissue concentrations, 68% in the liver concentrations and 86% in the kidney concentrations of the four fish species. Secondly, the concentration of Cu in muscle tissue from DR and SR whitefish, perch and pike had decreased significantly over the same time period in all three lake localities that could be compared (Fig. 16). Again, the reductions were large-sized, amounting to 75% both in Kuetsjarvi and Vaggatem and to 91% in Skrukkebukta.

More detailed descriptions of the results from the heavy metal analyses of fish are presented in Appendices 2-8.
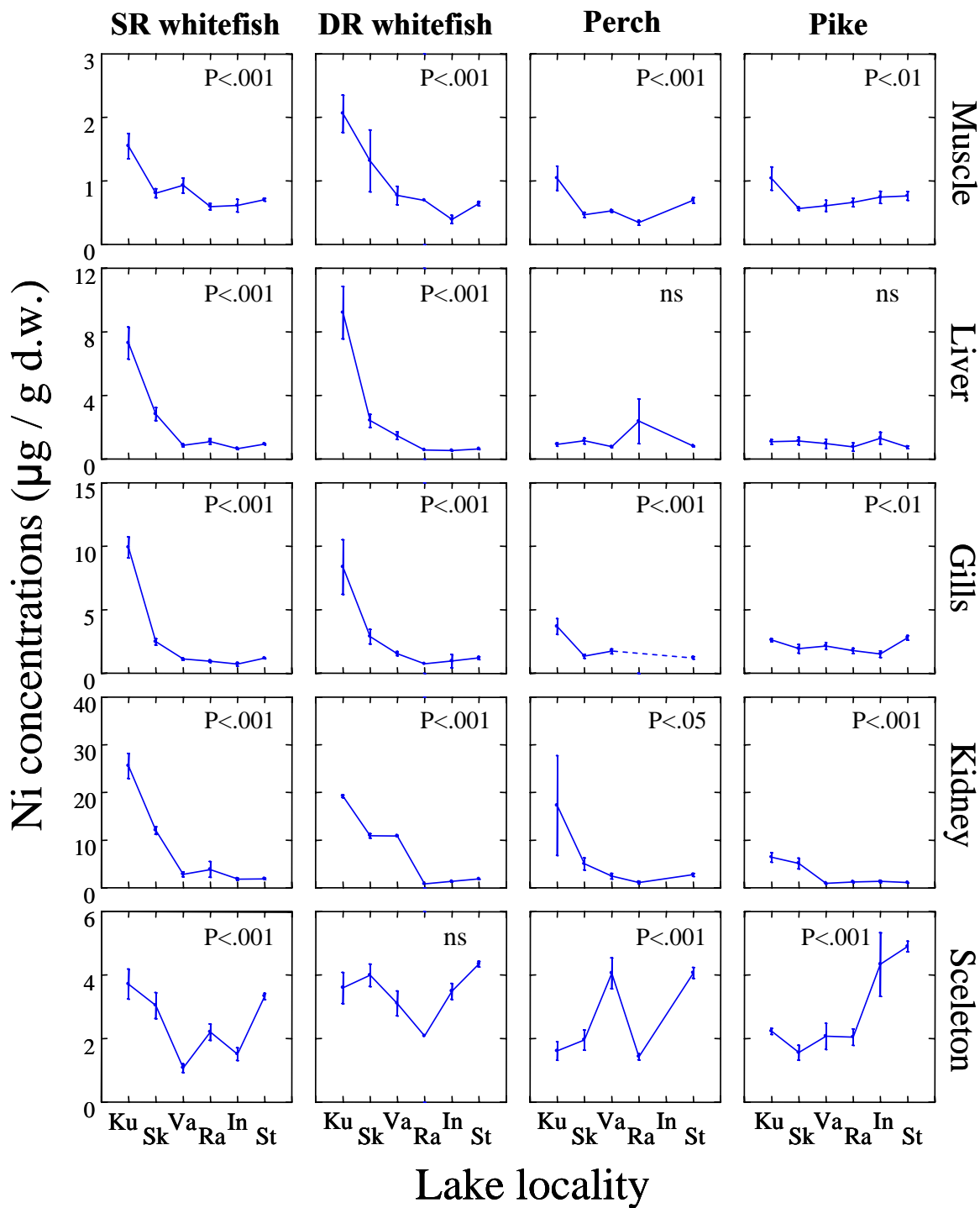
Fig. 12: Ni concentrations in different organs of SR and DR whitefish, perch and pike in lake localities with increasing distance to the Petchenganickel metallurgic smelters. Ku – Kuetsjarvi, Sk – Skrukkebukta, Va – Vaggatem, Ra – Rajakoski, In – Lake Inari, and St – Stuorajavri. Vertical bars indicate S.E. Test results (P-values) of Kruskal-Wallis tests are provided in each figure panel (ns = non- significant).
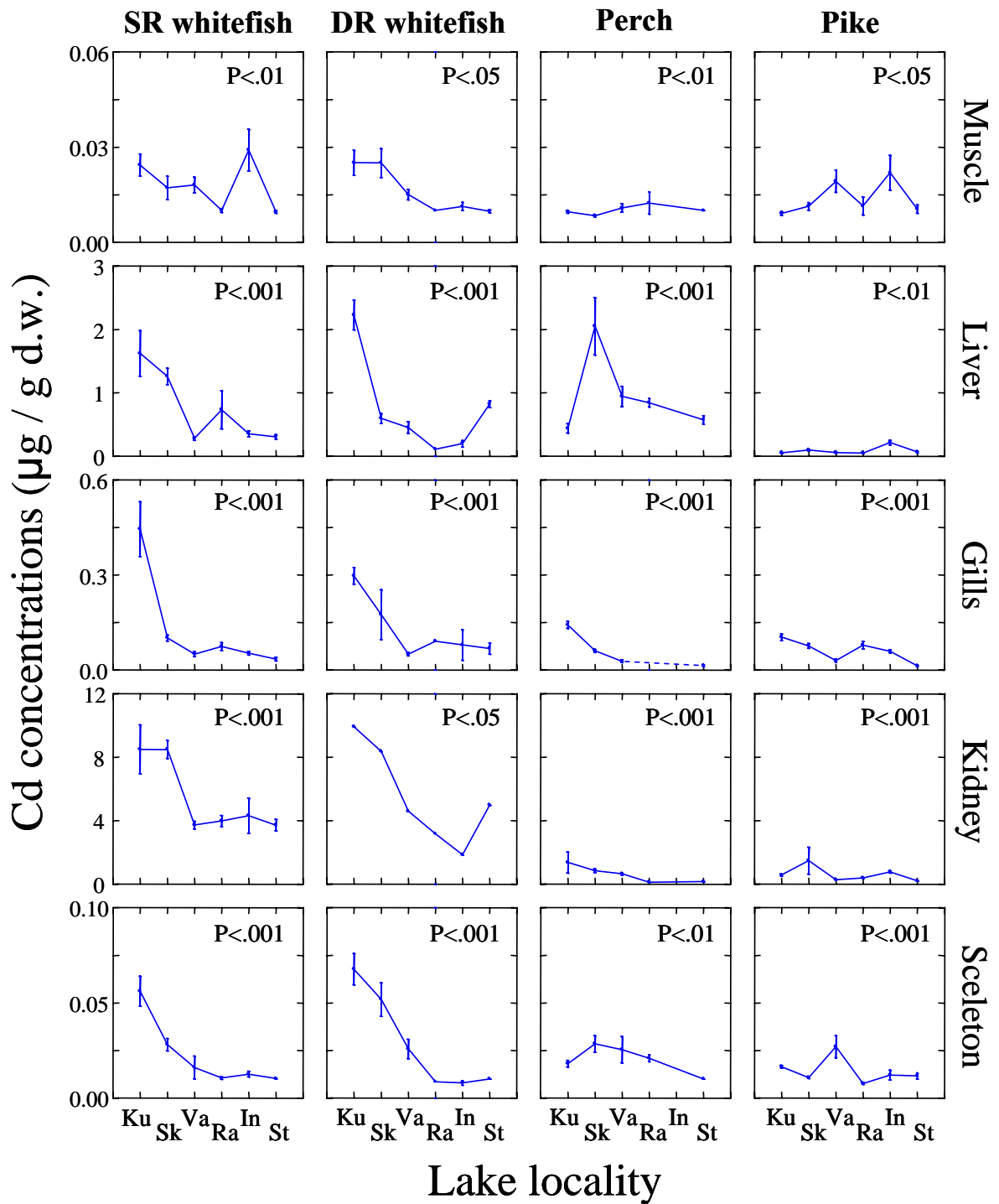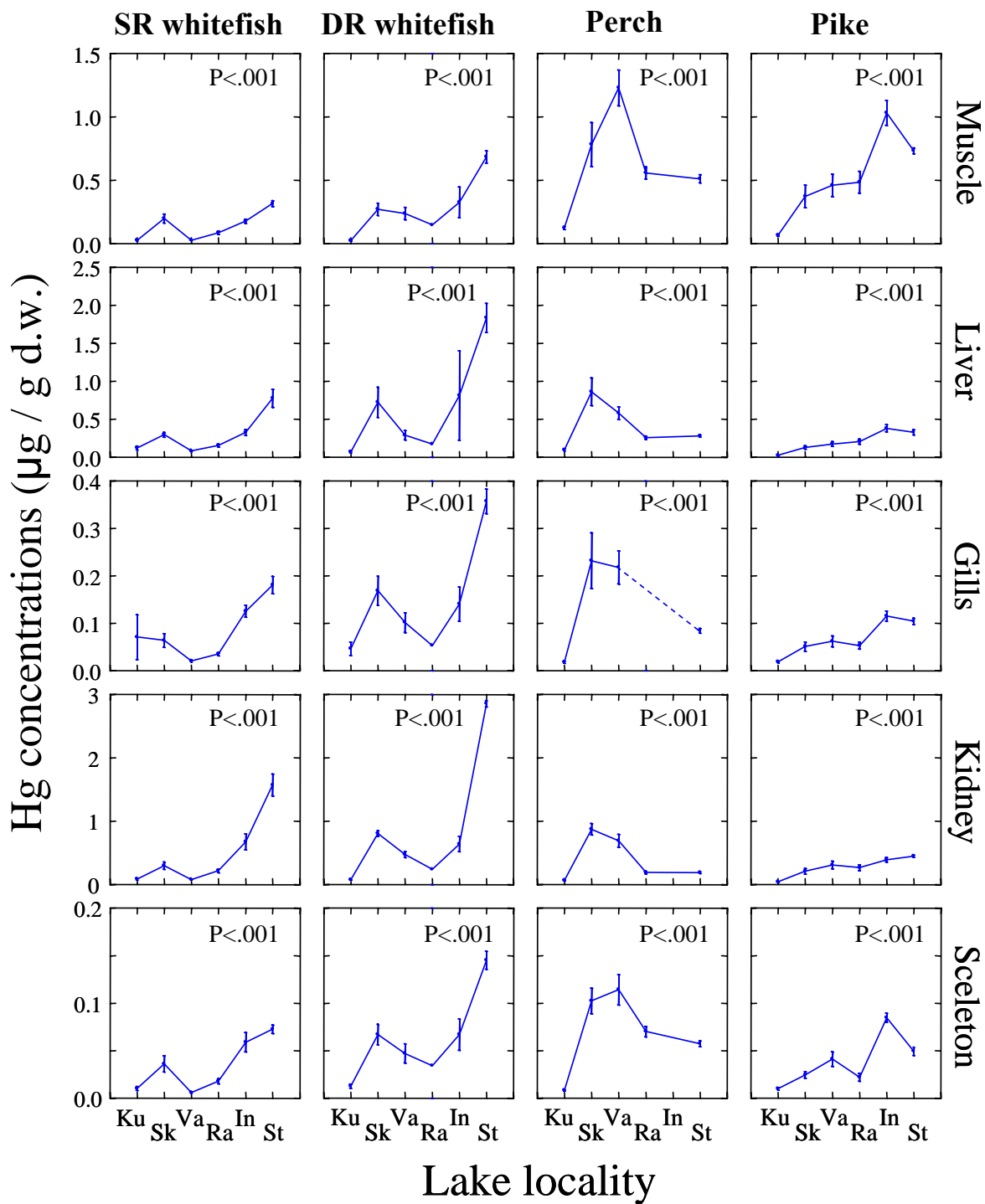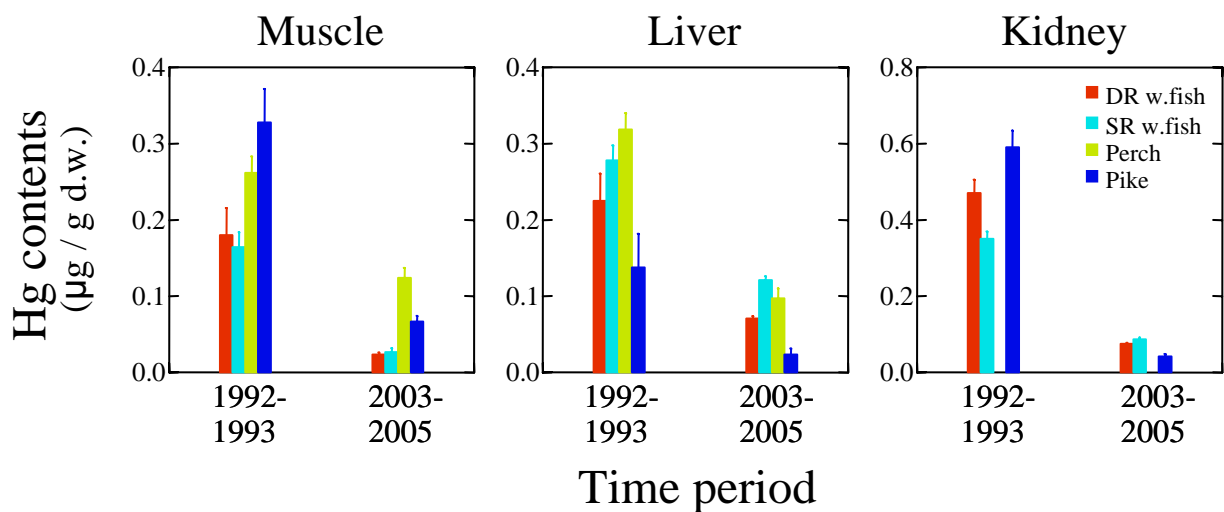
Fig. 13: Cd concentrations in different organs of SR and DR whitefish, perch and pike in lake localities with increasing distance to the Petchenganickel metallurgic smelters. Ku – Kuetsjarvi, Sk – Skrukkebukta, Va – Vaggatem, Ra – Rajakoski, In – Lake Inari, and St – Stuorajavri. Vertical bars indicate S.E. Test results (P-values) of Kruskal-Wallis tests are provided in each figure panel (ns = non- significant).

Fig. 14: Hg concentrations in different organs of SR and DR whitefish, perch and pike in lake localities with increasing distance to the Petchenganickel metallurgic smelters. Ku – Kuetsjarvi, Sk – Skrukkebukta, Va – Vaggatem, Ra – Rajakoski, In – Lake Inari, and St – Stuorajavri. Vertical bars indicate S.E. Test results (P-values) of Kruskal-Wallis tests are provided in each figure panel (ns = non- significant).

Fig. 15: Comparison of the Hg concentrations in different organs of SR and DR whitefish, perch and pike sampled in Kuetsjarvi in 1991-1992 and 2003-2005, respectively. Lines indicate S.E.
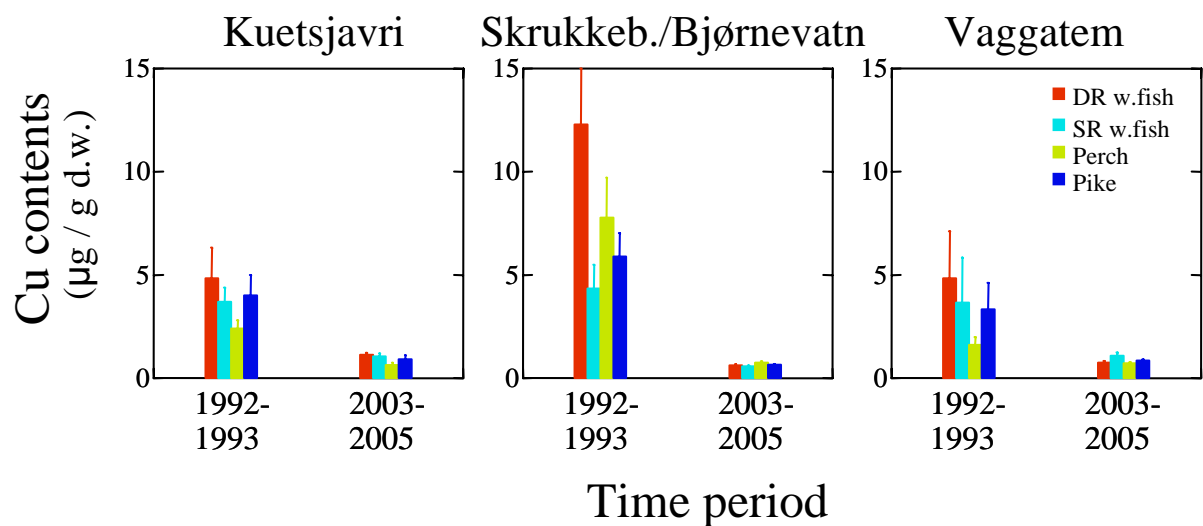
Fig. 16: Comparison of the Cu concentrations in muscle tissue of SR and DR whitefish, perch and pike sampled in 1991-1992 and 2003-2005, respectively. Lines indicate S.E.

4.5. Pathological effects

The visually recorded changes in fish organs and tissues in the studied lake localities can be summarized and illustrated as follows: (Fig. 17 - 25):

Fig. 17.Changes of muscle and liver coloration of pike.

Fig. 18. Changes of oral cavity coloration of pike

Fig. 19. Underdeveloped maxillary of whitefish (left image) and pike (right image).
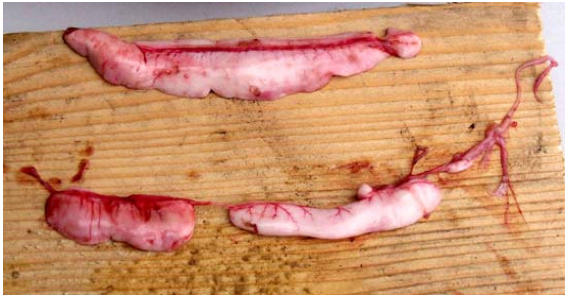
Fig. 20. "Segmentation" of gonads of male and female whitefish because of fibrogenesis

Fig. 21. Wrinkled form of gonads of male perch because of fibrogenesis development
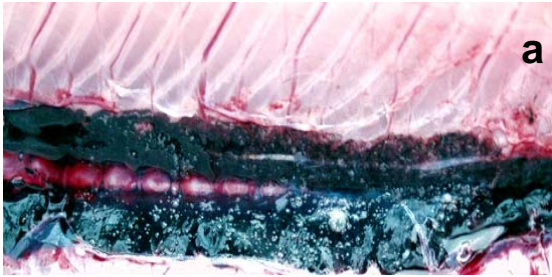
Fig. 22. Initial (a) and terminal (b) stage of fibrogenesis development in kidney of whitefish and (c) – nephrolithiasis.

Fig. 23. Twisted vertebrae of whitefish

Fig. 24. Early maturation of female and male whitefish and asymmetry of gonads

Fig. 25: Extreme degree of pathologic transformations of whitefish organs in the lake Kuetsjarvi (gelatiniforme of gonads; pale color of liver, sliming and pale color of gills, connective-tissue expansions in kidney, fatty heart and parasitic invasions on liver and heart)

The most common and serious disorders in the inner organs of whitefish were recorded in fish from Kuetsjarvi (Fig. 19, 20b, 20c, 21, 22, 23, 26), and for all organs there was a general decrease in the prevalence and severity of pathologifal changes with decreasing distance to the Nikel smelters (Fig. 26). Some increased levels were however observed in the reference locality Stuorajavri, but this was most likely related to the old age composition of whitefish caught in this lake. In Kuetsjarvi, the highest prevalences of pathological changes were seen in gonads, kidneys and liver. Disorders in the reproductive system were particularly frequent, including segmentations and other unnatural structures of especially the male gonads (Fig. 20), a phenomenon that was also observed in perch from this lake (Fig. 21). In total, more than 90 % of the whitefish in Kuetsjarvi suffered from pathological changes in the gonads, whereas less than 10 % of the whitefish in the other lake localities exhibited such disorders. Nephrolithiasis (kidney stones) was furthermore only recorded in whitefish from Kuetsjarvi with a prevalence of 9 % (Fig. 22c, 26). All whitefish from this locality also showed depigmentation of the skin and decreased turgor of the muscles. A more detailed description of the results from the pathological studies is given in Appendix 9.
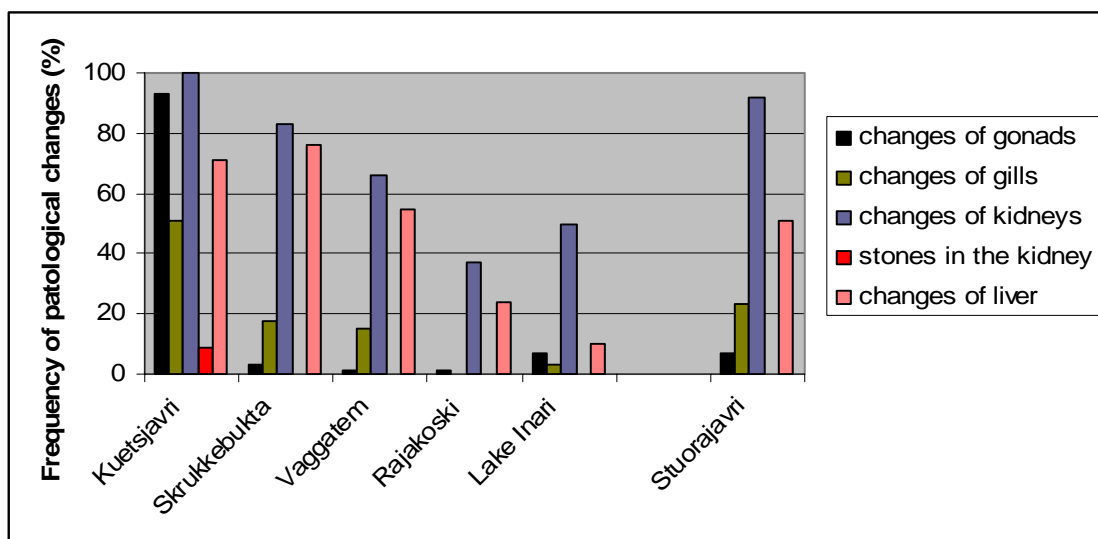
Fig. 26. Frequency of pathologic changes in inner organs of whitefish in lake localities in the Inari-Paz watercourse (2004) and in Stuorajavri (2005).

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5. Discussion

The studied lake localities had similar fish community structures and were all dominated by polymorphic whitefish and to some extent also by perch. However, in Skrukkebukta, Vaggatem and Lake Inari the introduced non-native vendace had become the dominant species in the pelagic habitat, having induced major ecological changes in these lake ecosystems (see also Amundsen et al. 1999, Bøhn & Amundsen 2001, Salonen et al. 2006). The main impacts of vendace are related to a relegation of DR whitefish from the pelagic habitat and a subsequent decline in whitefish population abundance (Amundsen et al. 1999, Bøhn & Amundsen 2001, Amundsen & Bøhn 2003). In Kuetsjarvi, however, the population density of vendace was still moderate and constituted less than 20% of the total fish density in the pelagic zone. The DR whitefish was the dominant pelagic fish species in this lake as was also seen in Stuorajavri, where vendace is not present. This is also typical for other lakes with polymorphic whitefish (Amundsen et al. 2004b). More surprisingly, however, the DR whitefish also dominated in the littoral zone in Kuetsjarvi. This contrasts the findings from the other studied lakes where SR whitefish and perch dominated the fish community in the littoral habitat. The DR and SR whitefish in Kuetsjarvi also differed from the populations in the other lake localities by having very slow individual growth rates and were dominated by small-sized fish. The whitefish populations in Kuetsjarvi also matured at an earlier age and a smaller size, and had in general a shorter longevity than whitefish in the other study lakes. The perch in Kuetsjarvi had in contrast the highest growth rate observed among the studied lakes. This may partly be related to the presence of small-sized whitefish prey, although the main reason appeared to be a high availability of nine-spined sticklebacks, which are highly suitable prey fish for perch (Bøhn et al. 2002, Amundsen et al. 2003).

Typically the two whitefish morphs have highly segregated habitat and diet niches with DR whitefish feeding mainly on zooplankton in the pelagic and SR whitefish mainly on zoobenthos in benthic habitats (Amundsen et al. 2004a,b). This was also generally seen in the present study, but in the lakes with a high presence of vendace the DR whitefish were feeding less on zooplankton, especially among the larger size-classes. Vendace is a specialized plankton predator and was in all lakes feeding mainly on crustacean zooplankton in the pelagic zone. Brown trout was the dominant pelagic fish predator in the studied lakes, feeding mainly on vendace and DR whitefish. Perch, pike and burbot were the dominant piscivore species in the benthic habitats, having nine-spined sticklebacks and SR and DR whitefish as their dominant fish prey. All these predatory species undergo distinct ontogenetic niche shifts during their life cycles. Brown trout are for example residing in tributary rivers and brooks and feed on zoobenthos during their first years of life, but start feeding on coregonid prey soon after their entrance into the lake systems. Perch feed on zooplankton in their first year of life, but switch to zoobenthos and later to nine-spined sticklebacks and finally to whitefish as they grow larger. Similar patterns are also seen for pike and burbot, and these ontogenetic niche shifts contribute together with the high fish diversity to compose complex and highly interactive food webs in the lakes of the Inari-Paz watercourse.

For the majority of the examined heavy metals there was a distinct increasing trend in metal contents in fish tissue with decreasing distance from the smelters, with highly elevated concentrations o heavy metals being found in fish from Kuetsjarvi. This trend was particularly pronounced in whitefish. For e.g. the nickel contamination in the two whitefish morphs, there was a >2-fold increase in the mean contents in muscle tissue, and an approximately 10-fold increase in the contents in liver, gills and kidney tissue from the reference lake Stuorajavri to Kuetsjarvi close to the smelters. Similar increases were also seen for Cd, and to less pronounced extents also for Mn, Al, Sr, Cu and Pb. The high levels of heavy metals in fish

from Kuetsjarvi reflect the elevated levels of heavy metals that have been found in water and sediment in the vicinity of the Pechenganikel smelters (e.g. Duvalter 1992, 1994, Moiseenko et al. 1995; and studies carried out during the present InterReg project). Both deposition of atmospheric emissions from the smelters and direct runoff from slag piles and mines may contribute to the metal contaminations in the Inari-Paz watercourse. Pollutants may also be transported downstream by the water flow, although rapid sedimentation probably restrains this mode of heavy metal dispersal. For most metals a rapid decline in water and sediment concentrations with increasing distance from the smelters has been demonstrated (Duvalter 1992, 1994; Moiseenko et al. 1995; and studies carried out during the present InterReg project), and this pattern was also seen for the heavy metal contaminations in fish. Hence, elevated levels of heavy metal contaminations in fish appear mainly to be a problem in Kuetsjarvi in the vicinity of the smelters, whereas the contamination levels rapidly decline with increasing distance and particularly upstream in the watercourse.

The only contrasting result with respect to an increasing trend in heavy metal contamination with decreasing distance from the smelters was found for mercury (Hg), which generally exhibited the lowest levels in the tissue of whitefish from Kuetsjarvi and the highest in fish from Stuorajavri. Hg is one of few heavy metals that are know to undergo biomagnification (e.g. Jernlöv & Lann 1971, Särkkä et al. 1978, Mason 1991), and thus typically tend to increase in concentration upwards in the food chain or with increasing age and size of the fish. The whitefish populations in Stuorajavri were dominated by old fish compared to the other lakes, and in particular compared to Kuetsjarvi, and this may therefore partly explain the higher Hg levels in this lake. There may on the other hand also be a local pollution source of Hg near Stuorajavri, potentially related to e.g. former mining activity in the catchment area of this lake, but further studies would be needed in order to explore this more specifically. From the present study we can however conclude that Hg in contrast to Ni and Cd and most other heavy metals, did not exhibit elevated contamination levels in fish from the vicinity of the Nikel smelters.

The heavy metal contamination levels in fish tissues were found to be of similar magnitude when comparing the investigated fish species, but the Ni and Cd contents were usually highest in whitefish whereas the Hg contents in muscle tissue were highest in perch and pike. Large differences were however observed between tissues. The lowest concentrations were consistently found in muscle tissue, where the observed metal levels in general did not exceed established quality standards for fish flesh (but critical limits for heavy metal levels in fish for human consumption are scarce!). Some individuals caught in Kuetsjarvi did however have considerably high levels in the fish flesh of certain elements. The largest heavy metal levels were found in the liver, gills and kidney of the fish, where the concentrations usually were several times higher than in the flesh. Particularly high levels were observed in Kuetsjarvi, and especially the Ni and Cd concentrations exhibited a strong increase in the vicinity of the smelters. The contamination levels of Ni and Cd and also several other metals were highest in the liver, which is known to be an important detoxification centre in fish (McFarlane & Franzin 1980). Nickel may be harmful to the survival and productivity of freshwater fauna (Moore & Ramamoorthy 1984), but studies of effects of Ni accumulation in fish are scarce (Sreedevi et al. 1992). Cadmium is a persistent element that may be toxic to aquatic organisms at relatively low concentrations, but Tylor (1980) considered the bioconcentration of Cd in aquatic vertebrates to be so low that it was likely of little significance. Dallinger et al. (1987), in contrast, pointed out that most heavy metals are effective at very low concentrations, so even low assimilation rates may be sufficient to attain biologically significant or even harmful concentrations in tissue. From the present study, there are several indications that the fish populations in Kuetsjarvi may suffer

from pollution stress related to elevated heavy metal contamination. At the individual level, pathological anomalies including changes of the gonads, kidneys, gills and liver were more prevalent and severe in Kuetsjarvi than in the other studied lake localities. There was also in general a gradual decrease in the incidence of pathological disorders of the fish with increasing distance to the smelters. The occurrence of pathological changes thus exhibited a strong correlation with the contamination levels of heavy metals like e.g. nickel, copper and cadmium, suggesting a causal relationship between fish pathology and heavy metal pollution. Similar findings have also been made in previous studies in the Inari-Paz watercourse (Langeland 1993, Moiseenko et al. 1995, Kashulin et al. 1997). At the population level, the present findings of slow growth rates, early sexual maturation and short longevity of the whitefish morphs in Kuetsjarvi compared to the other study lakes may represent life-history responses to heavy metal contamination. At the fish community level, indications of pollution stress are less obvious, but the unordinary habitat distribution of the whitefish morphs and the slow development in the vendace population density in Kuetsjarvi compared to the other lake localities in the Inari-Paz watercourse, may suggestively be related to the elevated heavy metal levels near the smelters.

In contrast to the large spatial variations in heavy metal concentrations in fish, the temporal variations were less pronounced. Over the three years of study included in the present investigations in Skrukkebukta and Vaggatem, there were usually only moderate variations in the heavy metal contaminations of the fish, although some important short-term changes also were observed. The long-term comparison between 1991-92 and 2003-2005 did however demonstrate some considerably large and highly significant changes in heavy metal contents. In particular, the levels of Hg and Cu strongly decreased, demonstrating that a continued monitoring of the heavy metal levels in fish is important, especially in respect to a renovation and modernization program for the Nikel smelters in order to decrease the pollution output. Annual variations in heavy metal concentrations in fish may also be expected to be larger in the vicinity of the smelters, like e.g. in Kuetsjarvi, where the pollution impact is largest.

6. Conclusions and recommendations for a joint monitoring program

The present study demonstrates a large influence of the Petchenga-Nikel smelters on the heavy metal concentrations in freshwater fish in the lower parts of the Inari-Paz watercourse. For most metals, a steep gradient in contamination levels were seen with increasing distance form the smelters, with highly elevated levels in Kuetsjarvi in the vicinity of the smelters compared to the more distant study localities. The elevated levels of heavy metal contaminations may represent a problem for the fish populations, especially in Kuetsjarvi where potential symptoms of pollution stress were observed both at the individual, population and community levels. In particular, the pathological studies demonstrated that serious changes had occurred in tissue and organs of fish from Kuetsjarvi. The population studies furthermore suggested life-history responses to the pollution impacts in terms of earlier maturation, diminished growth rates and short longevity, especially in whitefish. Heavy metals are regarded as potential hazards that can endanger both animal and human health (Duffus 1980, Mance 1987). Knowledge of their concentrations in fish is therefore important both with respect to nature monitoring and the management of freshwater fish populations for human consumption. A continued survey of the ecology, pathology and heavy

metal contaminations of selected fish populations along a gradient of increasing distance to the metallurgic smelters will provide a detailed and important insight into the development of the environmental conditions in the region, and we therefore recommend that this is included in the planned monitoring program for the border areas. The monitoring studies should be carried out with a maximum of three years intervals, and preferably with only two years intervals in localities in the vicinity of the pollution sources. A spatial gradient of four lake localities should be included in the monitoring, including Kuetsjarvi, Skrukkebukta, Vaggatem and Lake Inari. Analyses should comprise basic ecological surveys of fish, fish pathology studies and sampling of tissue for heavy metals analyses from whitefish, perch and pike. The ecological analyses of fish should include parameters such as fish species composition, population structure, somatic growth, and sexual maturation. Heavy metal samples should be retrieved from muscle, liver, gills and kidney from a minimum of 10-20 specimens of each fish species at each locality, and the analyses should include Ni, Cu, Cd, Mn, Al, Sr, Pb and Hg. Pathological studies should be carried out on whitefish, perch and pike, and include analyses of gonads, gills, kidneys, and liver. The fish sampling should also be coordinated with sampling of water and sediments for chemical analyses including heavy metals. The monitoring in Lake Inari may preferably be coordinated with the ongoing management surveys of the fish populations in the lake carried out by the Finnish Game and Fisheries Research Institute in Inari. The importance of continued environmental monitoring of the fish populations in the Inari-Paz watercourse can be summarized as: 1) freshwater fish are important resources for recreational, subsistence and commercial exploitation and human consumption in the watercourse; 2) fish are sensitive and conspicuous indicators of the environment quality; 3) severe impacts of the metallurgic industry have already been documented to occur; and 4) a renovation program for the Nikel smelters is expected to result in a significant decrease in the heavy metal pollution impacts in the watercourse, and these effects can most efficiently be monitored and documented by the suggested studies of fish.

7. Acknowledgements

8. References

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Appendix

Appendix 1. Heavy metal contaminations in fish – additional figures
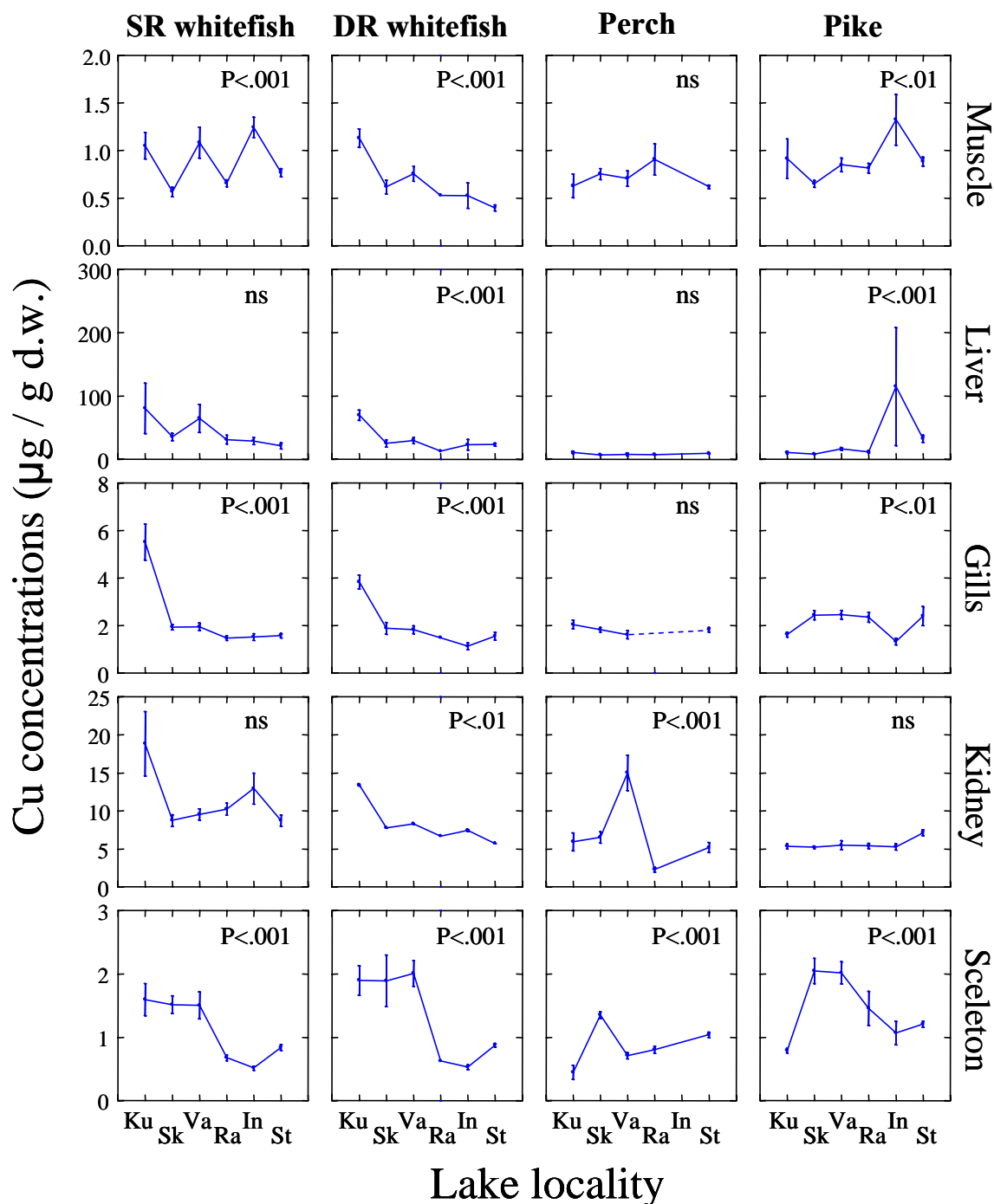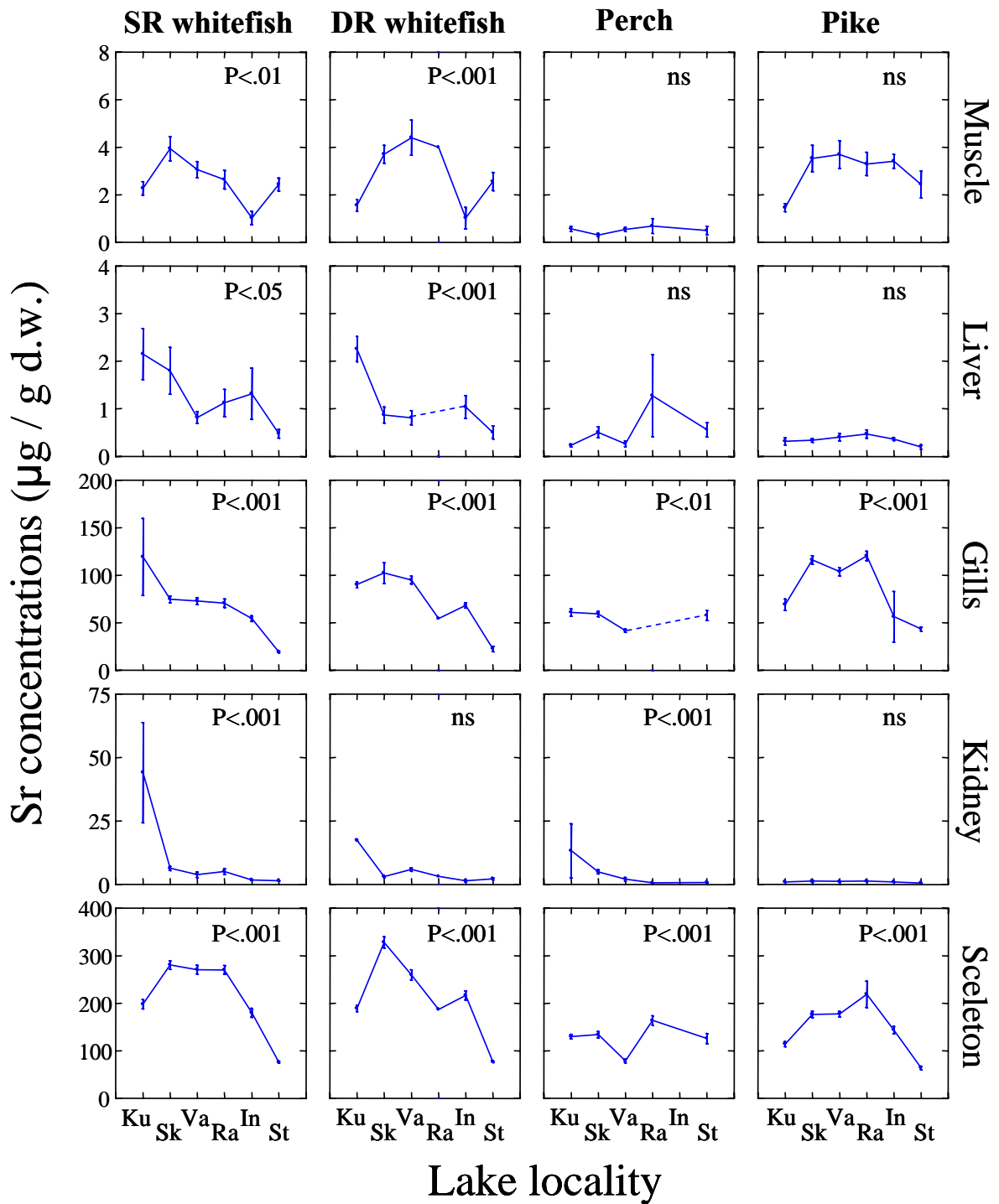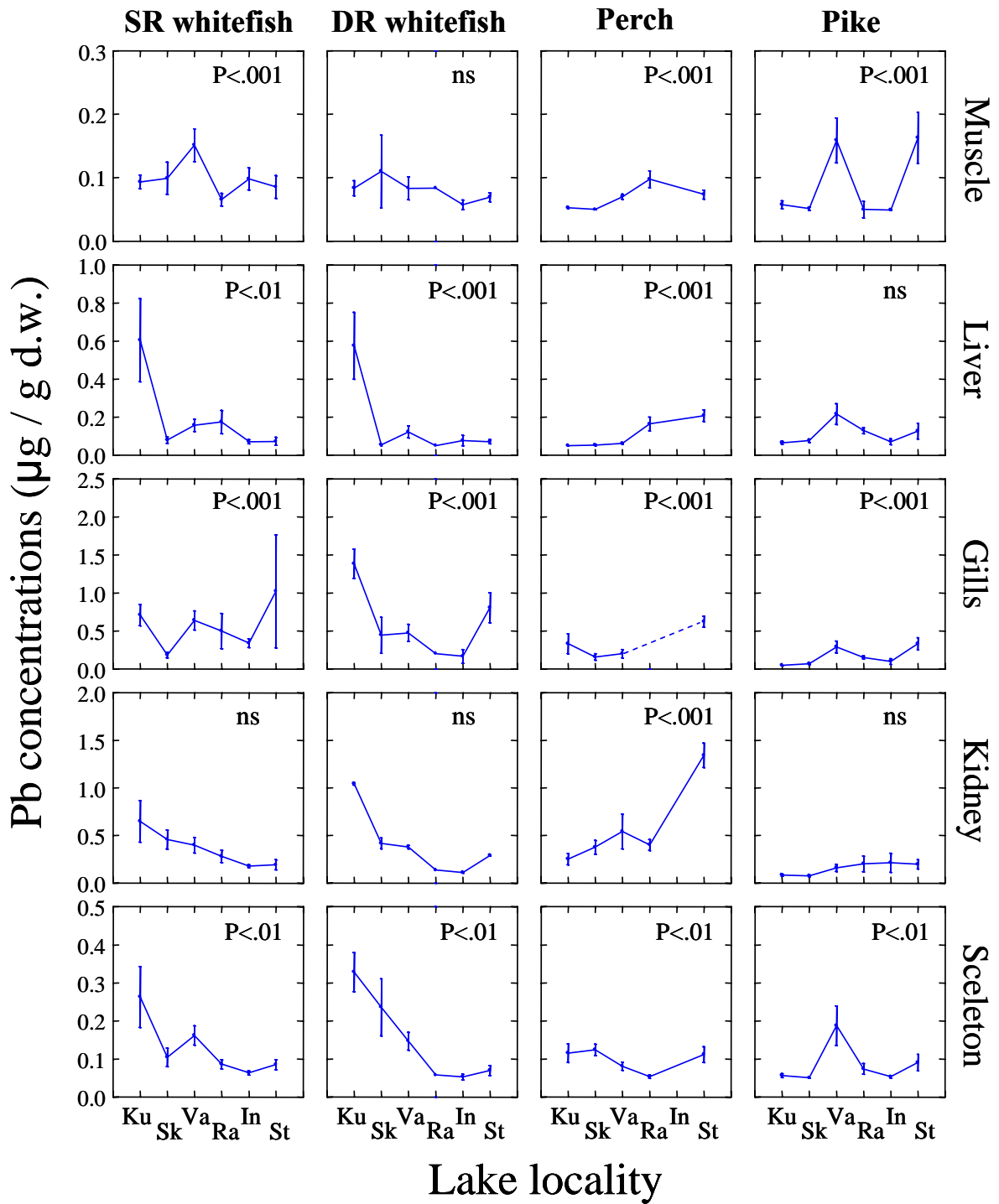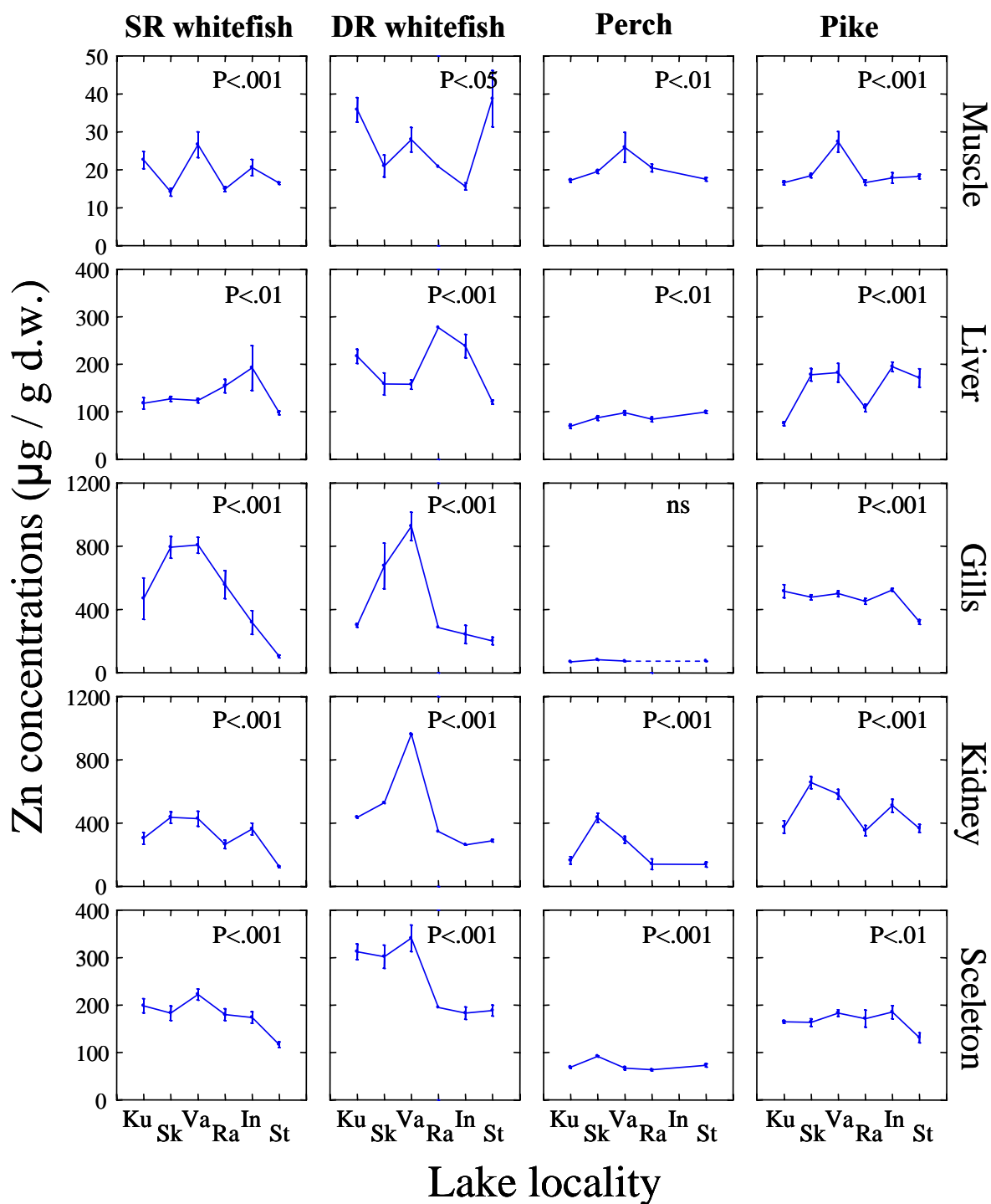

Fig. 1.1: Cu concentrations in different organs of SR and DR whitefish, perch and pike in lake localities with increasing distance to the Petchenganickel metallurgic smelters. Ku – Kuetsjarvi, Sk – Skrukkebukta, Va – Vaggatem, Ra – Rajakoski, In – Lake Inari, and St – Stuorajavri. Vertical bars indicate S.E. Test results (P-values) of Kruskal-Wallis tests are provided in each figure panel (ns = non- significant).
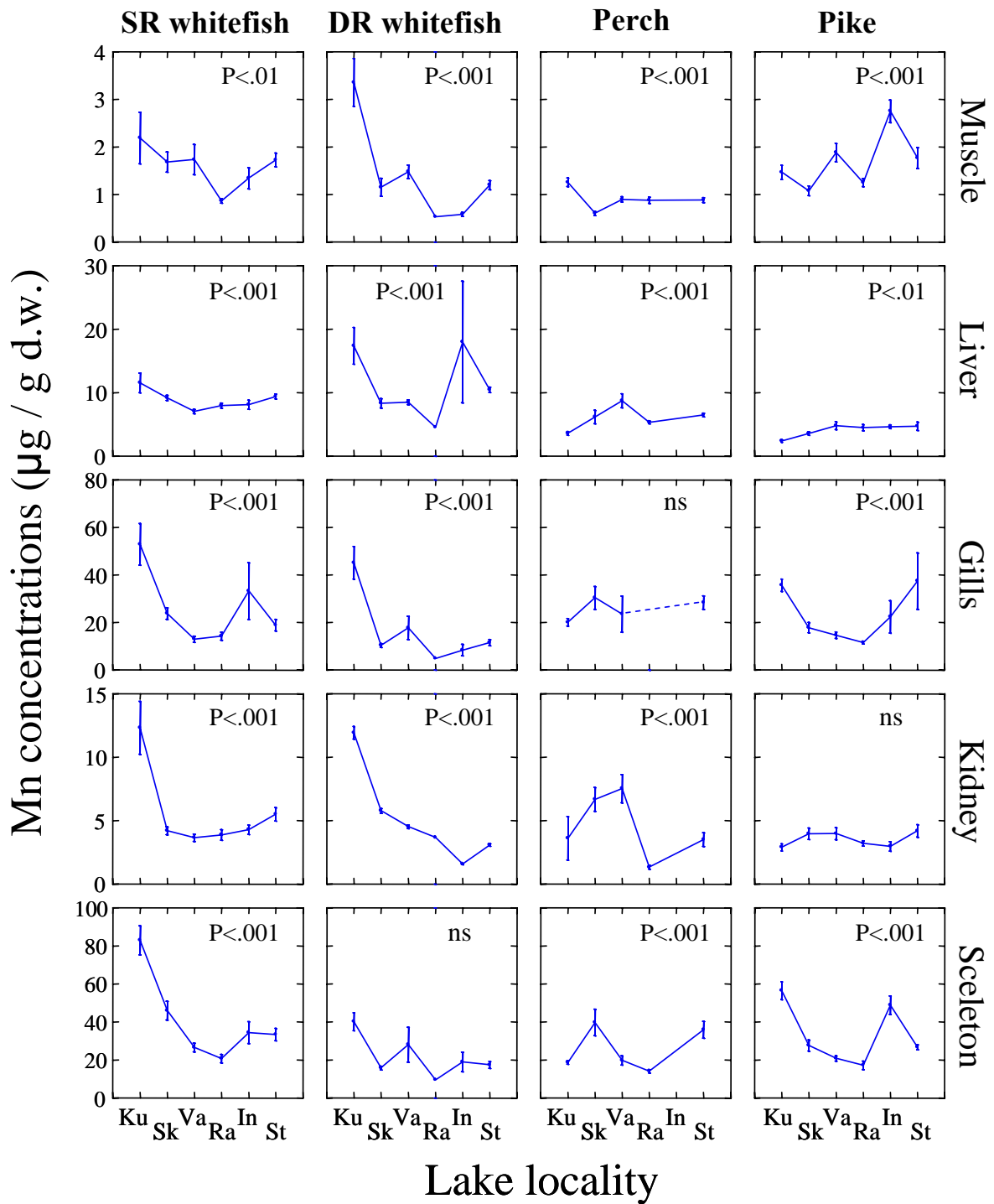
Fig. 1.2: Mn concentrations in different organs of SR and DR whitefish, perch and pike in lake localities with increasing distance to the Petchenganickel metallurgic smelters. Ku – Kuetsjarvi, Sk – Skrukkebukta, Va – Vaggatem, Ra – Rajakoski, In – Lake Inari, and St – Stuorajavri. Vertical bars indicate S.E. Test results (P-values) of Kruskal-Wallis tests are provided in each figure panel (ns = non- significant).
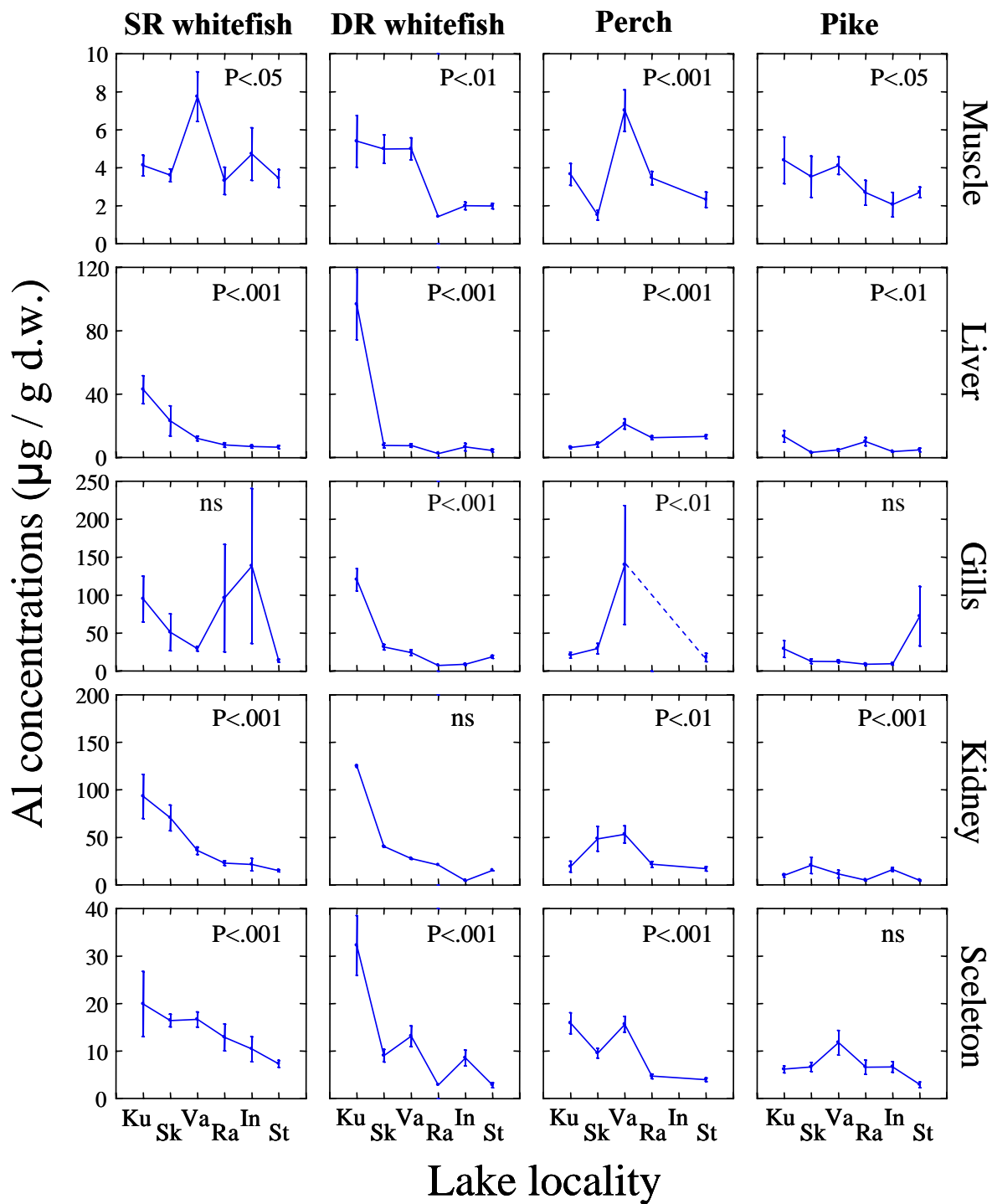
Fig. 1.3: Al concentrations in different organs of SR and DR whitefish, perch and pike in lake localities with increasing distance to the Petchenganickel metallurgic smelters. Ku – Kuetsjarvi, Sk – Skrukkebukta, Va – Vaggatem, Ra – Rajakoski, In – Lake Inari, and St – Stuorajavri. Vertical bars indicate S.E. Test results (P-values) of Kruskal-Wallis tests are provided in each figure panel (ns = non- significant).

Fig. 1.4: Sr concentrations in different organs of SR and DR whitefish, perch and pike in lake localities with increasing distance to the Petchenganickel metallurgic smelters. Ku – Kuetsjarvi, Sk – Skrukkebukta, Va – Vaggatem, Ra – Rajakoski, In – Lake Inari, and St – Stuorajavri. Vertical bars indicate S.E. Test results (P-values) of Kruskal-Wallis tests are provided in each figure panel (ns = non- significant).

Fig. 1.5: Pb concentrations in different organs of SR and DR whitefish, perch and pike in lake localities with increasing distance to the Petchenganickel metallurgic smelters. Ku – Kuetsjarvi, Sk – Skrukkebukta, Va – Vaggatem, Ra – Rajakoski, In – Lake Inari, and St – Stuorajavri. Vertical bars indicate S.E. Test results (P-values) of Kruskal-Wallis tests are provided in each figure panel (ns = non- significant).

Fig. 1.6: Zn concentrations in different organs of SR and DR whitefish, perch and pike in lake localities with increasing distance to the Petchenganickel metallurgic smelters. Ku – Kuetsjarvi, Sk – Skrukkebukta, Va – Vaggatem, Ra – Rajakoski, In – Lake Inari, and St – Stuorajavri. Vertical bars indicate S.E. Test results (P-values) of Kruskal-Wallis tests are provided in each figure panel (ns = non- significant).

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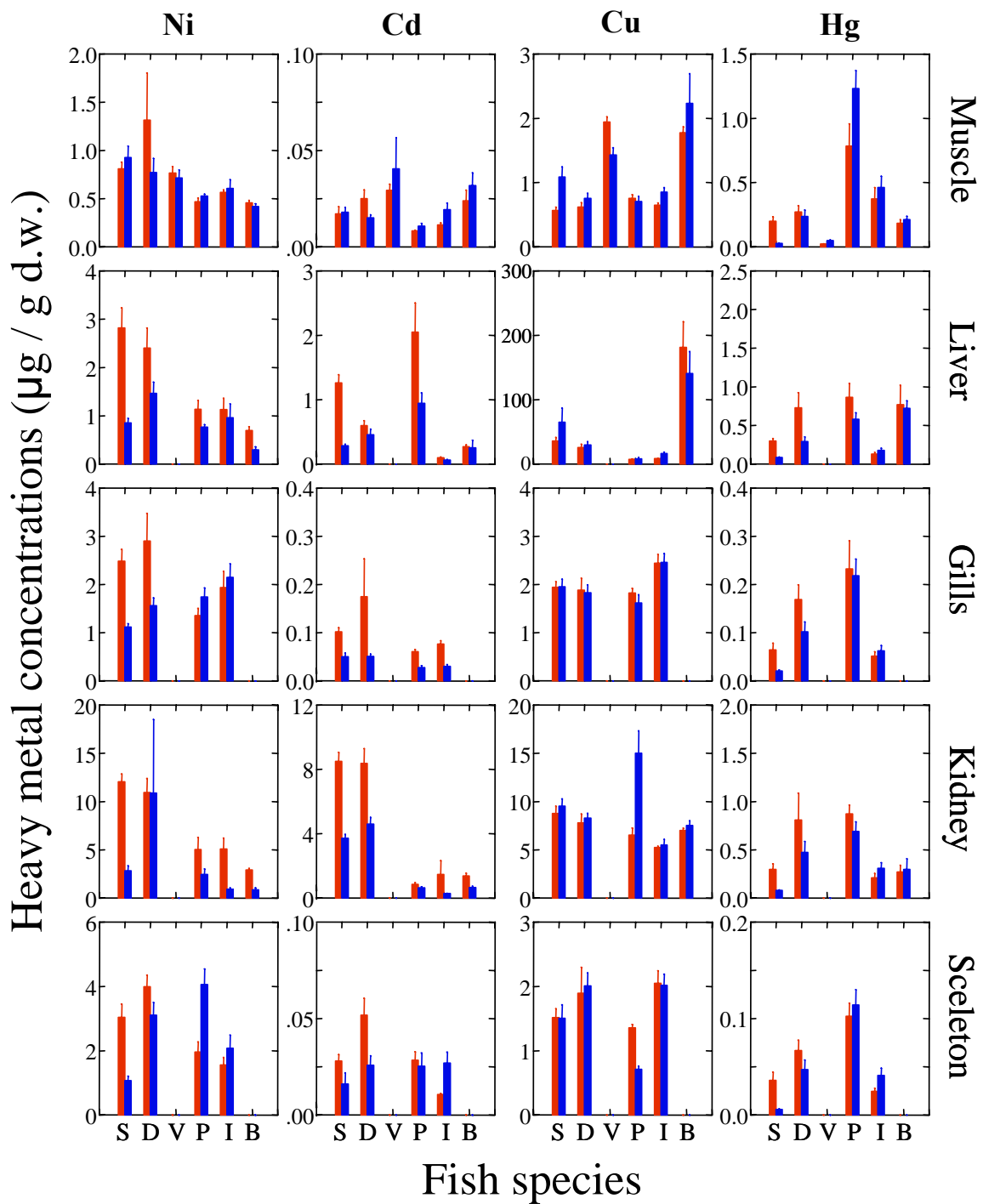
Fig. 1.7: Comparisons of heavy metal concentrations (Ni, Cd, Cu, Hg) between SR whitefish (S), DR whitefish (D), vendace (V), perch (P), pike (I) and brown trout (B) from Skrukkebukta (red bars) and Vaggatem (blue bars). Lines indicate S.E.
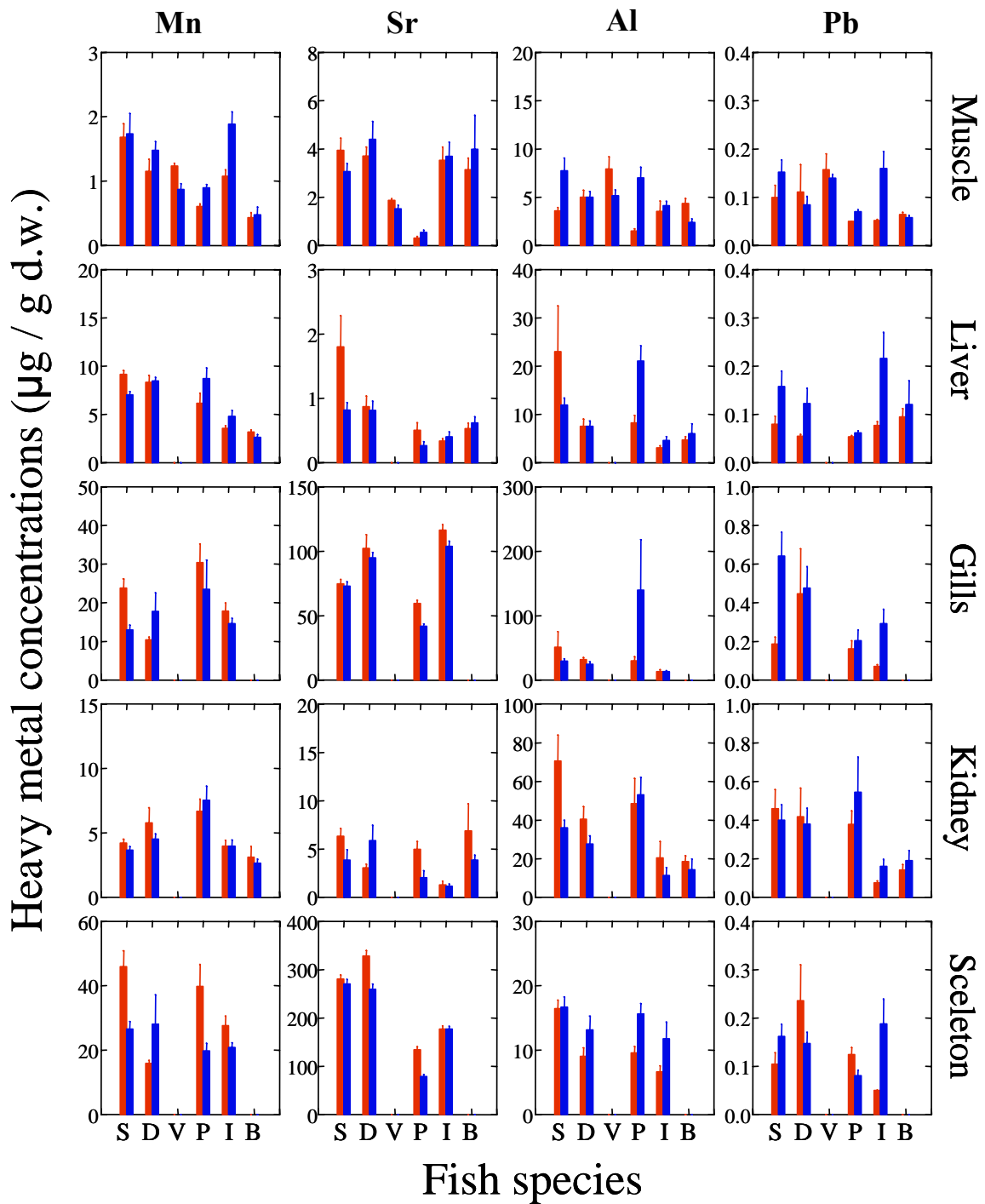
Fig. 1.8: Comparisons of heavy metal concentrations (Mn, Sr, Al, Pb) between SR whitefish (S), DR whitefish (D), vendace (V), perch (P), pike (I) and brown trout (B) from Skrukkebukta (red bars) and Vaggatem (blue bars). Lines indicate S.E.

Appendix 2. Detailed presentation of heavy metal contaminations in different fish species

Whitefish

Copper. Both forms of whitefish inhabiting the water bodies of the Inari-Paz watercourse had comparable levels of heavy metal accumulation in body, despite different feeding habits. The concentrations of main pollutants of copper-nickel productions – Cu and Ni increased in liver and kidney of whitefish along the whole Inari-Paz watercourse in the direction of the source of pollution – the "Pechenganickel" smelter. Minimum mean values of copper concentration in liver of whitefish were found in fish from the lakes Inari and Rajakoski and maximum values were revealed in the lake Kuetsjarvi (Fig. 2.1). The district Skrukkebukta, located downstream the lake Kuetsjarvi is characterized by decreased copper contaminations. The densely rakered whitefish of the lake Kuetsjarvi had higher copper concentrations in liver in comparison with the sparsely rakered whitefish.
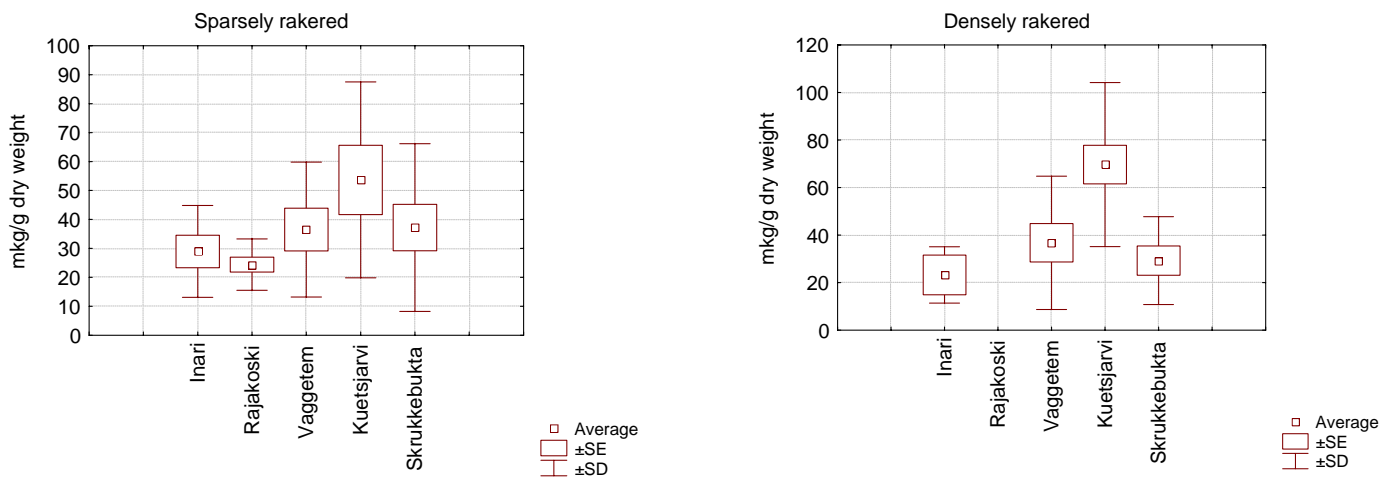
Fig. 2.1. Copper concentrations in liver of sparsely and densely rakered whitefish in the water bodies of the Inari-Paz watercourse in 2004.

Nickel. Ni accumulation in kidney of whitefish had similar distribution pattern. But in comparison with copper contaminations in liver, mean Ni concentrations in kidney of the fish from the lakes Kuetsjarvi and Skrukkebukta were characterized by a sensible difference with the whitefish from the upstream and middle stream of the River Paz, where Ni concentrations didn't exceed 5 µkg/g dry wt (Fig. 2.2). On average these values of both forms of whitefish from the lakes Kuetsjarvi and Skrukkebukta were 10.5 and 6 times higher than in whitefish of the lake Inari, Rajakoski and Vaggetem. Maximum Ni concentrations in kidney of sparsely rakered whitefish reached 74.46 µkg/g dry wt.
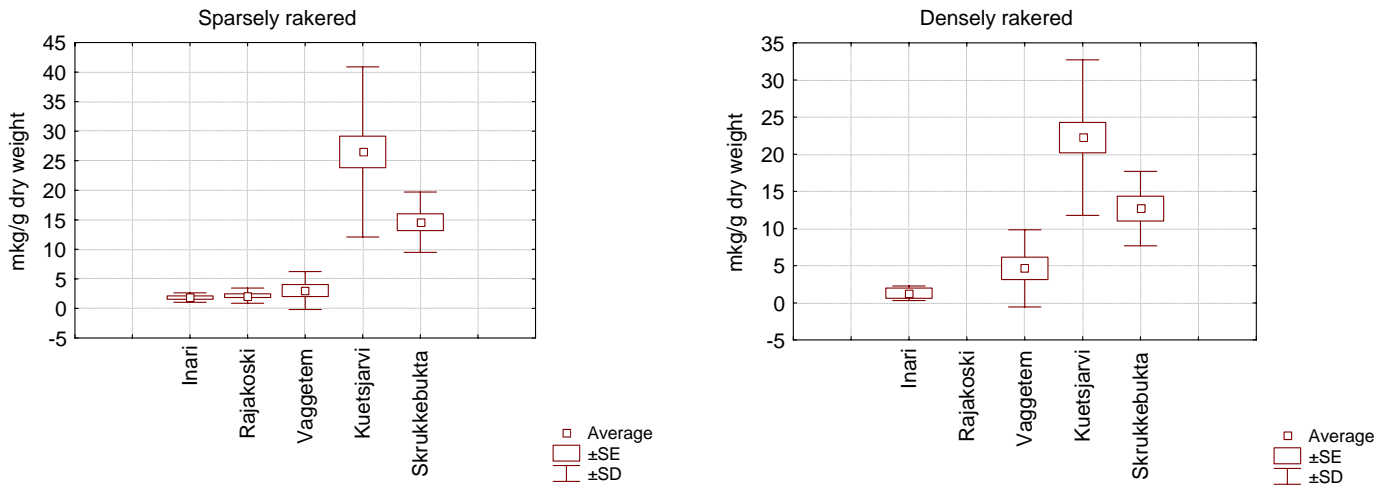
Fig. 2.2. Nickel concentrations in kidney of sparsely and densely rakered whitefish in the water bodies of the Inari-Paz watercourse in 2004.

Mercury. The actual notion of high mercury concentrations in the ecosystems of reservoirs was partially substantiated by data on mercury distribution in muscle tissue of whitefish. Minimum concentrations were registered in the lake Kuetsjarvi (0.03 – for the sparsely rakered and 0.02 μkg/g dry wt – for the densely rakered whitefish). At the same time, the mercury concentrations in muscle of sparsely rakered whitefish didn't exceed 0.03 μkg/g dry wt in the Vaggetem reservoir, and in the most remote district – the lake Inari reached 0.18 (s.r. whitefish) and 0.33 (d.r. whitefish) μkg/g dry wt (Fig. 2.3).
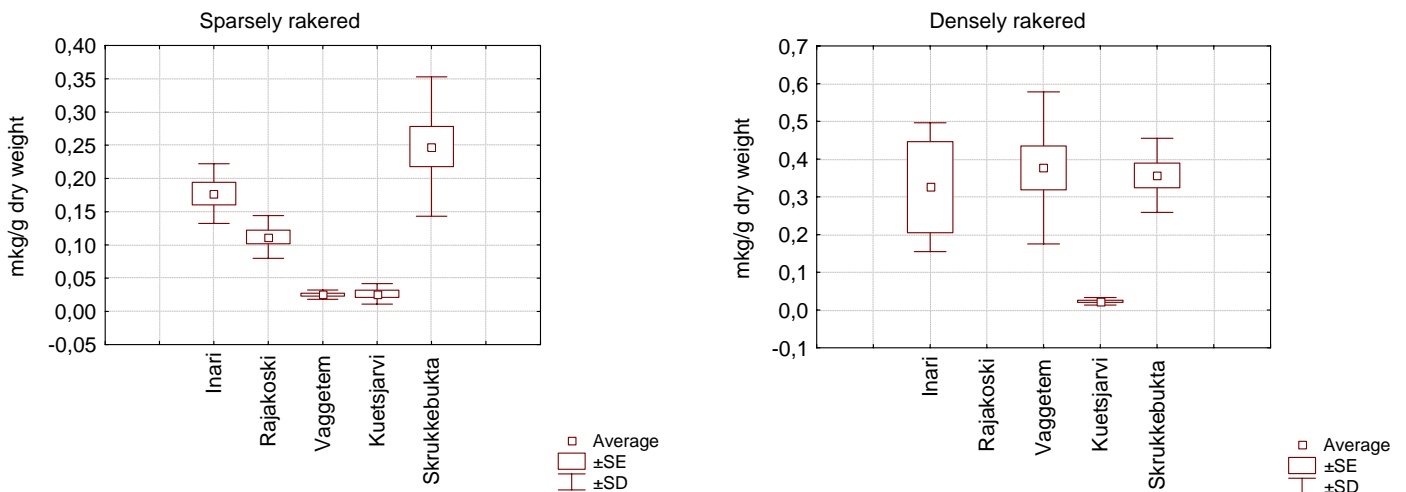
Fig. 2.3. Mercury concentrations in muscle of sparsely and densely rakered whitefish in the water bodies of the Inari-Paz watercourse in 2004.

This can be explained by the fact that the studies in the lake Inari were pursued in the vicinity of the Paz river headwater. The creation of the hydroelectric power system resulted in flooding of the headwater territory and this water can be referred to as a reservoir. Besides, it should be noted that the mercury concentrations in muscle of densely rakered whitefish-planktonophage were higher. With the exception of the catch from the lake Kuetsjarvi the other fish of this form had mean concentrations above 0.3 μkg/g dry wt.

Perch

Copper. Copper concentrations in liver of perch were lower compared to whitefish, but the metal distribution in liver had the similar pattern according to the source of pollution. Copper concentrations increased as follows: Rajakoski>Vaggetem>Kuetsjarvi and reduced in Skrukkebukta. Mean copper concentrations in liver of whitefish, except for the lake Kuetsjarvi ranged between 6 to 8 µkg/g dry wt (Fig. 2.4), it is on the whole smaller than in perch from the small forest lakes in 2005.
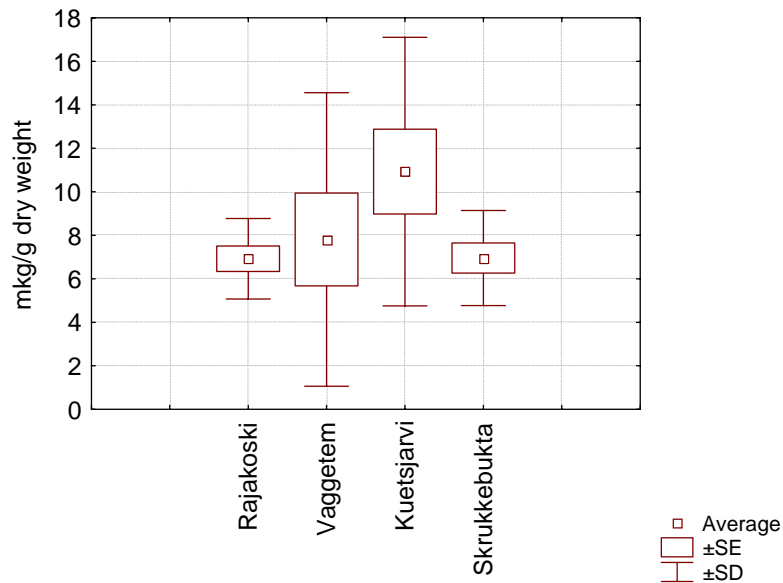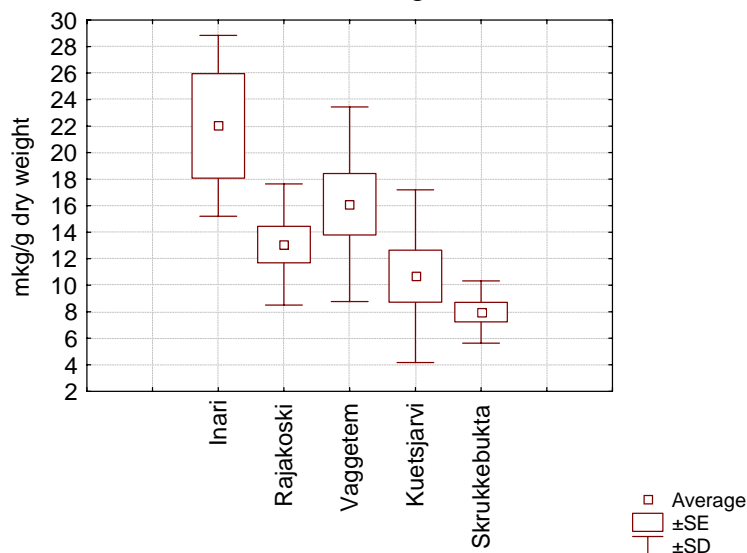

Fig. 2.4. Copper concentrations in liver of perch in the water bodies of the Inari-Paz watercourse in 2004.

Nickel. The same as for copper, maximum Ni concentrations and its range limits in kidney of perch were observed in the lake Kuetsjarvi. Minimum value was 0.26 and ultimate value – 14.68 µkg/g dry wt. The lower Ni concentrations were registered in perch of the Rajakoski district (Fig. 2.5). The perch of the Inari-Paz watercourse even in heavily polluted lake Kuetsjarvi had lower Ni concentrations than the perch of the small forest lakes.
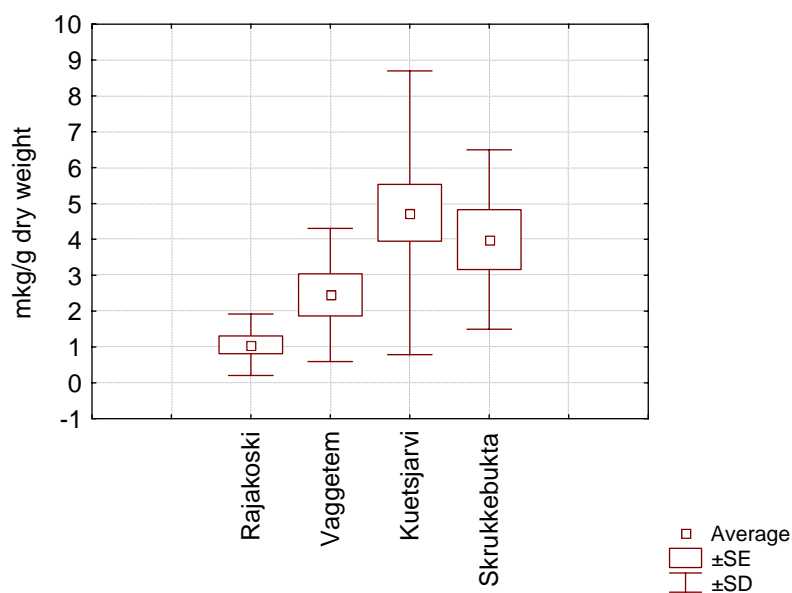
Fig. 2.5. Nickel concentrations in kidney of perch in the water bodies of the Inari-Paz watercourse in 2004.

Mercury. On the whole mercury concentrations in muscle of perch had the similar peculiarity, characterized by higher concentrations in the fish from the reservoirs. The highest mean concentrations in tissue of perch were registered in the district Vaggetem (1.23 μkg/g dry wt) and Skrukkebukta (0.78 μkg/g dry wt). Minimum values were observed in the perch form the lake Kuetsjarvi (Fig. 2.6). It should be noted that mercury accumulation in muscle of perch of the Inari-Paz watercourse, being chiefly reservoirs, was lower as compared to the perch of the small forest lakes on the territory of Finland and border area of Russia.
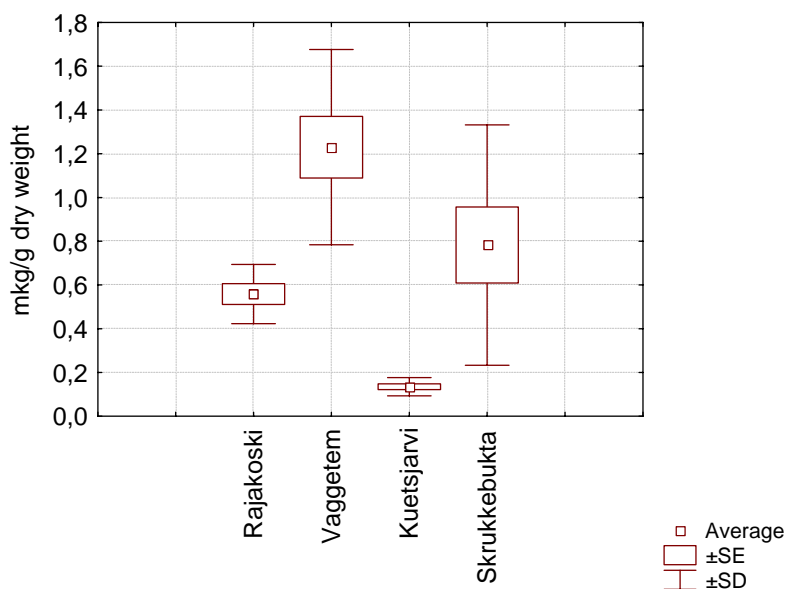
Fig. 2.6. Mercury concentrations in muscle of perch in the water bodies of the Inari-Paz watercourse in 2004.

Pike

Copper. Copper distribution in liver of pike was characterized by inverse dependence according to the "Pechenganickel" smelter. The highest mean copper concentrations were observed in pike of the lake Inari (22.02 µkg/g dry wt). Minimum values were registered in the district Skrukkebukta (Fig. 2.7). Copper concentrations in liver of pike from the Inari-Paz watercourse mediated between the whitefish and perch. As compared to the pike of the small forest lakes, metal concentrations in liver in this region were on the whole lower (Appendix).

Fig. 2.7. Copper concentrations in liver of pike in the water bodies of the Inari-Paz watercourse in 2004.

Nickel. As in above mentioned species, Ni accumulated more actively in kidney of pike inhabiting the lake Kuetsjarvi and in the district Skrukkebukta. The highest concentrations in kidney of pike in Kuetsjarvi and Skrukkebukta were 9.57 and 12.49 µkg/g dry wt respectively. Mean Ni concentrations in kidney of pike form the upstream and middle stream of the River Paz were 4 times lower and varied between 1.24 and 1.35 µkg/g dry wt (Fig. 2.8).

Mercury. The mercury accumulation in muscle of pike was dominated by the fish from the lake Inari (mean concentrations – 1.03 µkg/g dry wt) and Vaggetem (0.86 µkg/g dry wt). Minimum values of mercury accumulation in tissue were observed in the pike from the lake Kuetsjarvi (Fig. 2.9). Here mean concentrations were lower than the corresponding values of the pike from other water bodies and were equal to 0.07 µkg/g dry wt. It should be also pointed out that mercury concentrations in muscle of pike form the reservoirs of the Inari-Paz watercourse were lower as compared to the pike from the small forest lakes, where minimum values of mean mercury contamination of muscle were 1.25 µkg/g dry wt.

Nickel and copper distribution in fish organs in the Inari-Paz watercourse depended on the distance from the "Pechenganickel" smelter. The concentrations of these elements increased as the load was higher and were highest in the fish of the lake Kuetsjarvi. The pattern of mercury accumulation in muscle of fish proves the fact that in reservoirs the fish have higher levels of mercury accumulation. At the same time the mercury accumulation in tissue of fish from the small forest lakes were higher as compared to the fish from the Inari-Paz watercourse. The d.r. whitefish had higher mercury concentrations in tissue than s.r.

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whitefish. A similar peculiarity was observed for the d.r. whitefish of the background area (the lake Stuorajarvi).
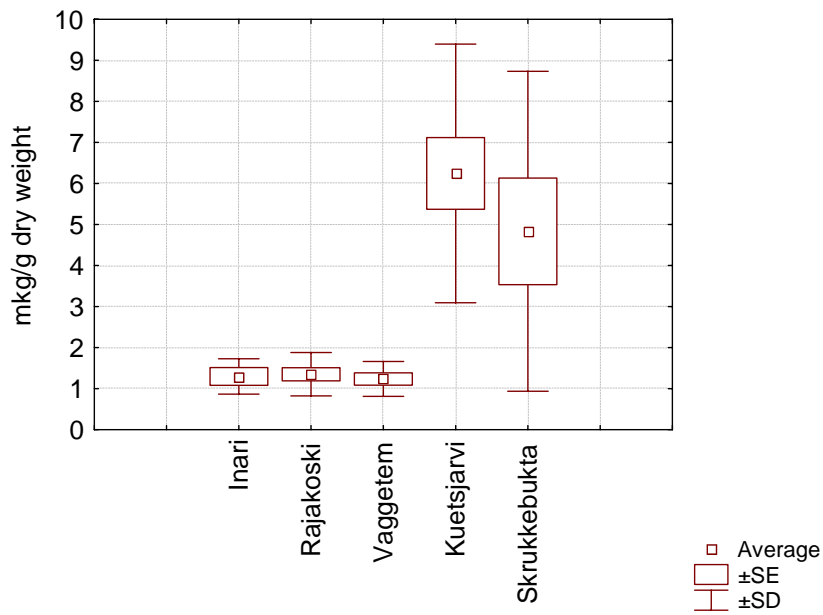

Fig. 2.8. Nickel concentrations in kidney of pike in the water bodies of the Inari-Paz watercourse in 2004.
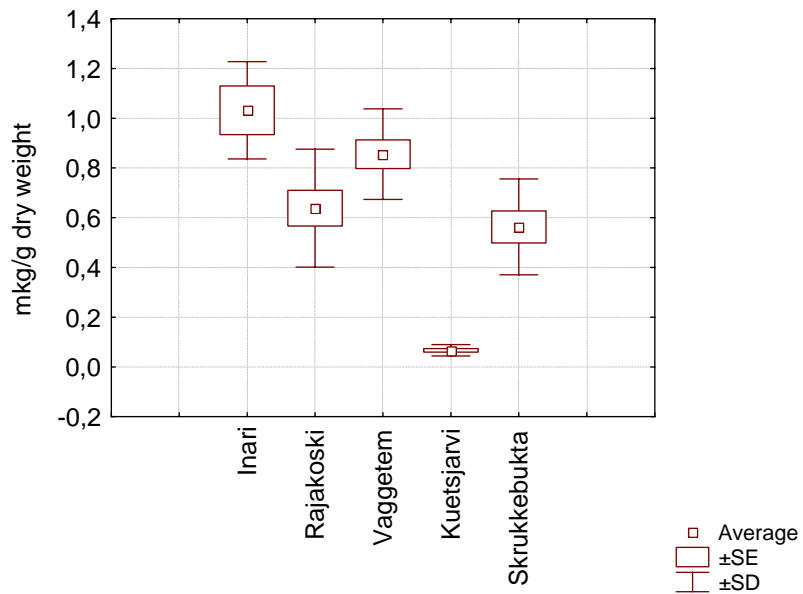

Fig. 2.9. Mercury concentrations in muscle of pike in the water bodies of the Inari-Paz watercourse in 2004.

Appendix 3. Detailed presentation of heavy metal contaminations in fish from Kuetsjarvi

Muscle. Cu concentrations in muscle of whitefish and pike differ insignificantly. The smallest value was registered for the perch. Ni concentrations varied from 1.0 to 2.1 $\mu kg/g^{-1}$ dry wt. The same value of the predatory fish species was 1.5 -2 times higher as of the whitefish. The highest zinc and manganese concentrations were observed in d.r. whitefish, the s.r. whitefish occupied intermediated position. Strontium accumulated in large quantities in muscle of s.r. whitefish and in small quantities – in perch. No differences were revealed between the d.r. whitefish and pike. The predatory species were characterized by higher capacity for mercury bioaccumulation (*Figure 3.1*).
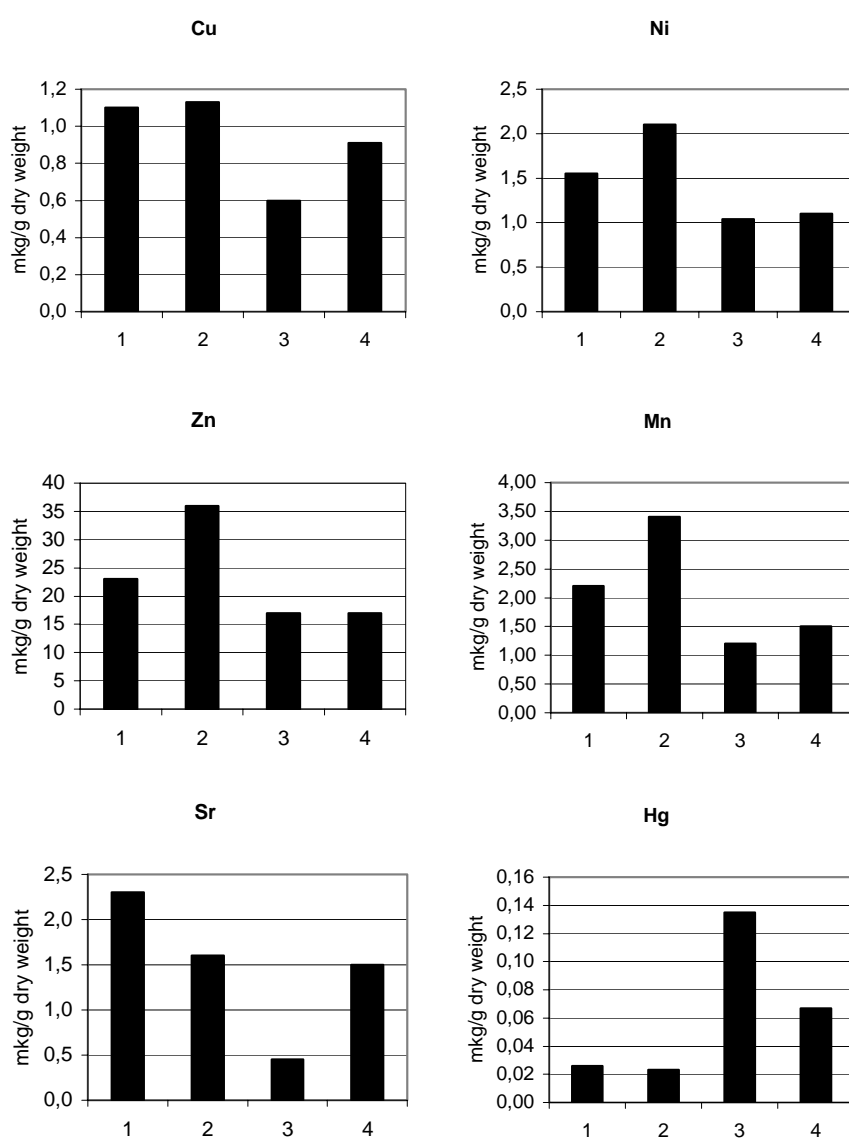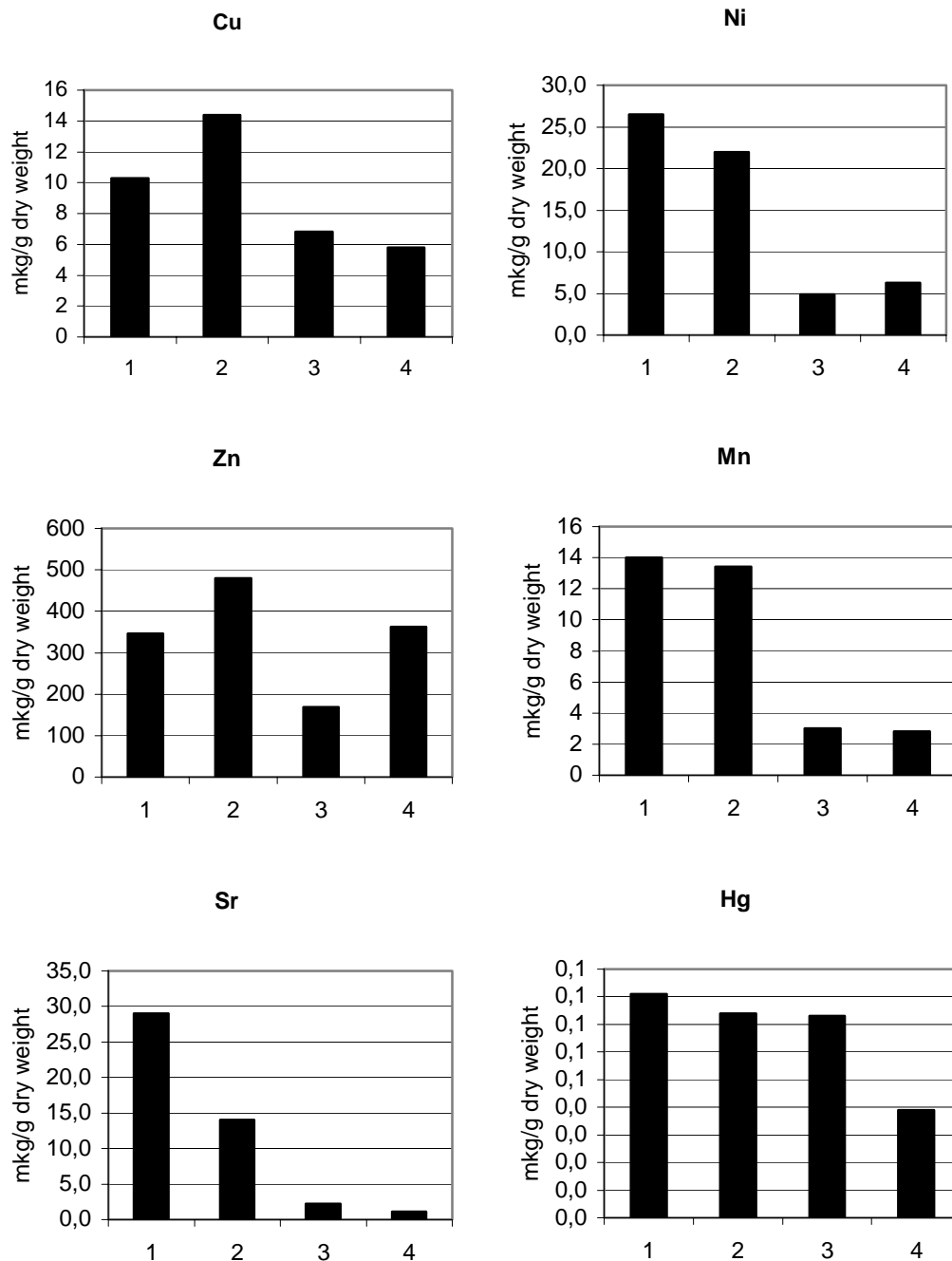

Figure 3.1. Heavy metal concentrations in muscle of fish of the Kuetsjarvi Lake in 2004 (1 – sparsely rakered whitefish, 2 – densely rakered whitefish, 3- perch, 4 - pike).

Liver. The content of Cu in both forms of whitefish was 5-7 times higher as in predatory fish. No differences were observed between the perch and pike. Ni concentrations submit to the same pattern. With mean Cu concentrations of 50-70 $\mu kg/g^{-1}$ dry wt, some individual samples had C_{Cu} equal to 511 $\mu kg/g^{-1}$ dry wt. Whitefish had higher level of zinc, manganese and strontium accumulation. The d.r. whitefish had higher concentrations of Zn and Mn in liver as compared to the s.r. whitefish. Perch had the highest mercury concentrations.
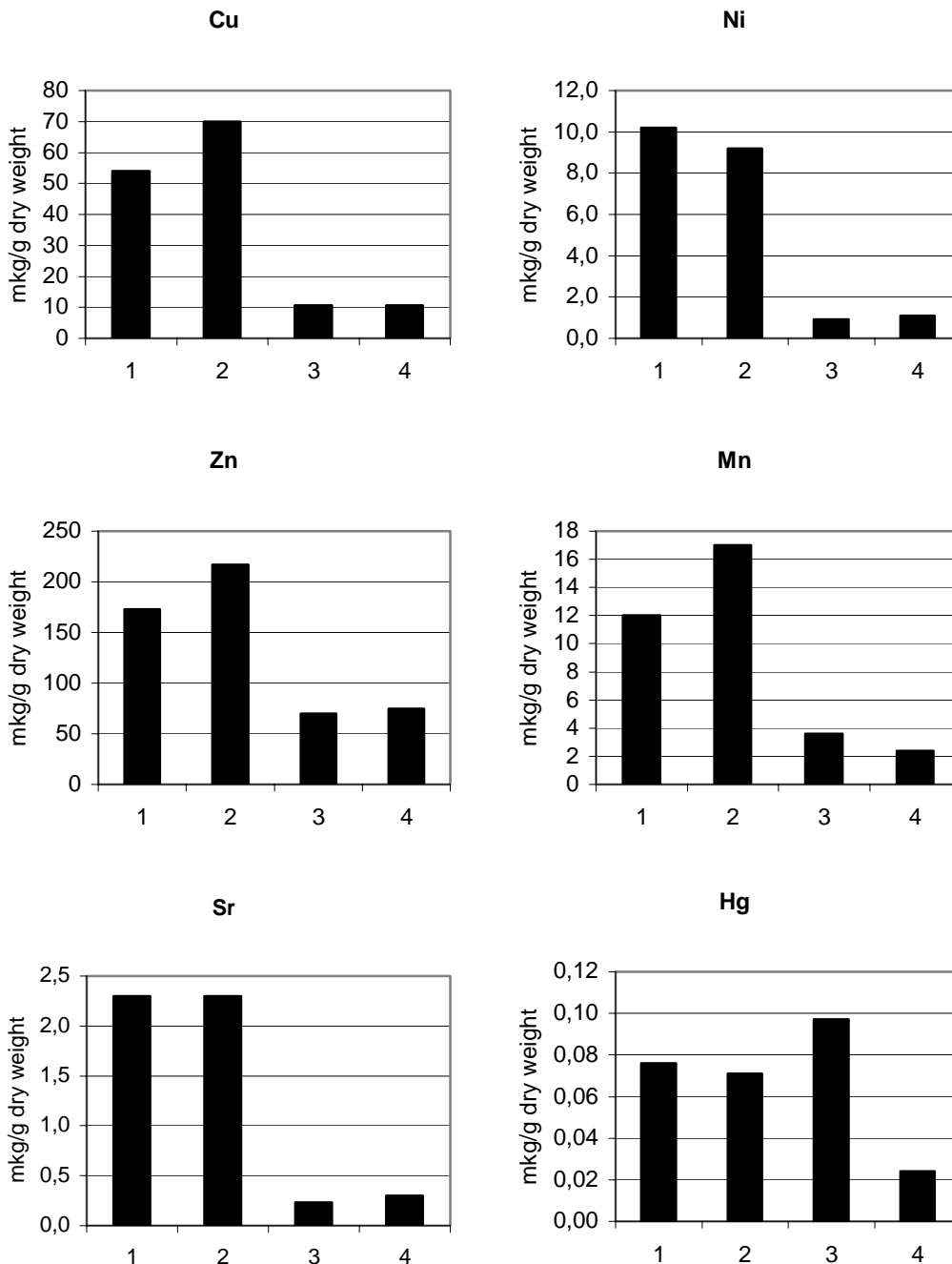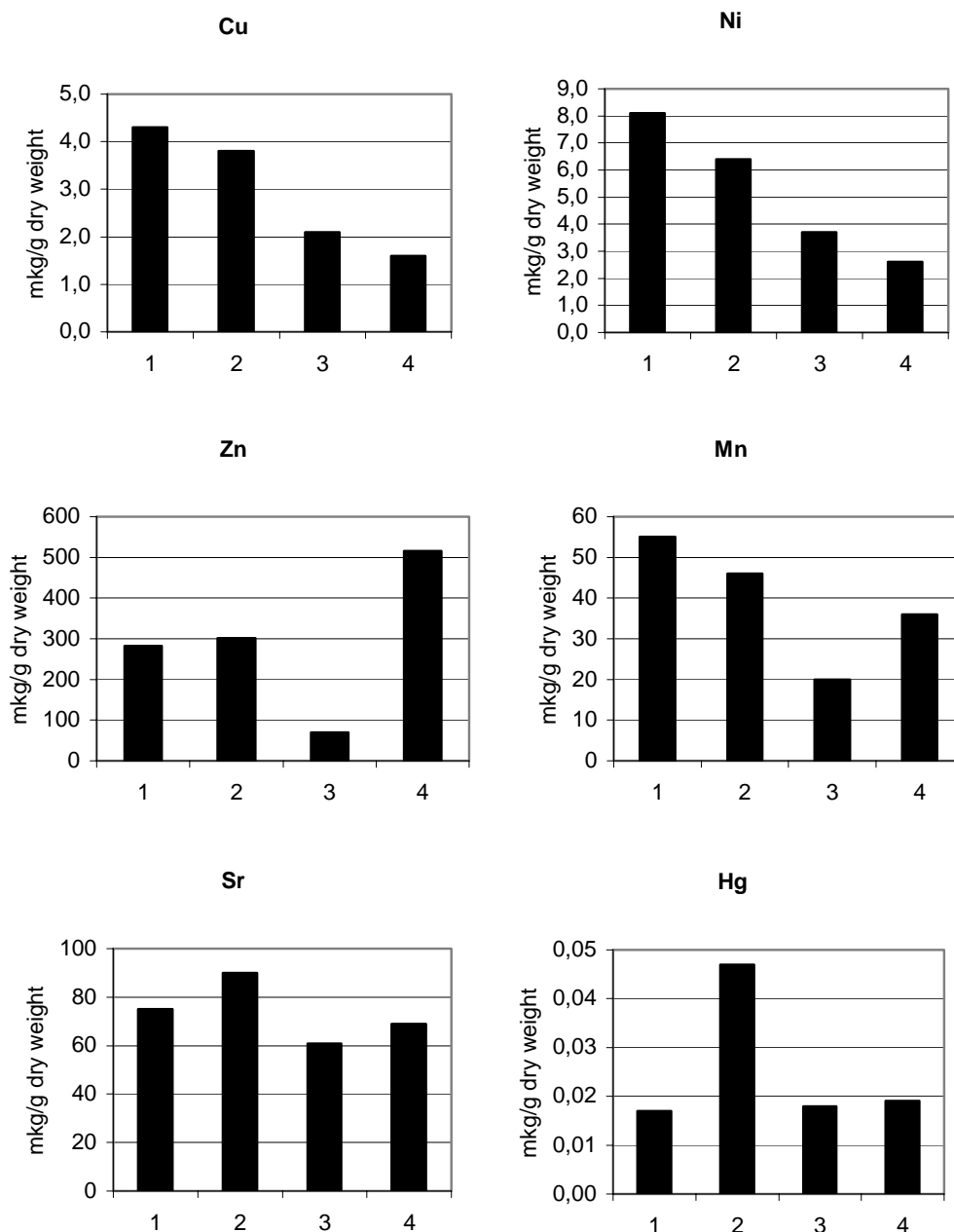

Figure 3.2. Heavy metal concentrations in liver of fish of the Kuetsjarvi Lake in 2004 (1 – sparsely rakered whitefish, 2 – densely rakered whitefish, 3- perch, 4 - pike).

Kidney. Some metals demonstrate a clear-cut species-specific character of accumulation in kidney. Except for zinc and mercury, the content of copper, nickel, manganese and strontium was several times higher in whitefish. Pike and s.r. whitefish don't indicate any differences in zinc concentrations. Perch and whitefish are characterized by a high level of mercury accumulation (*Figure 3.3*).
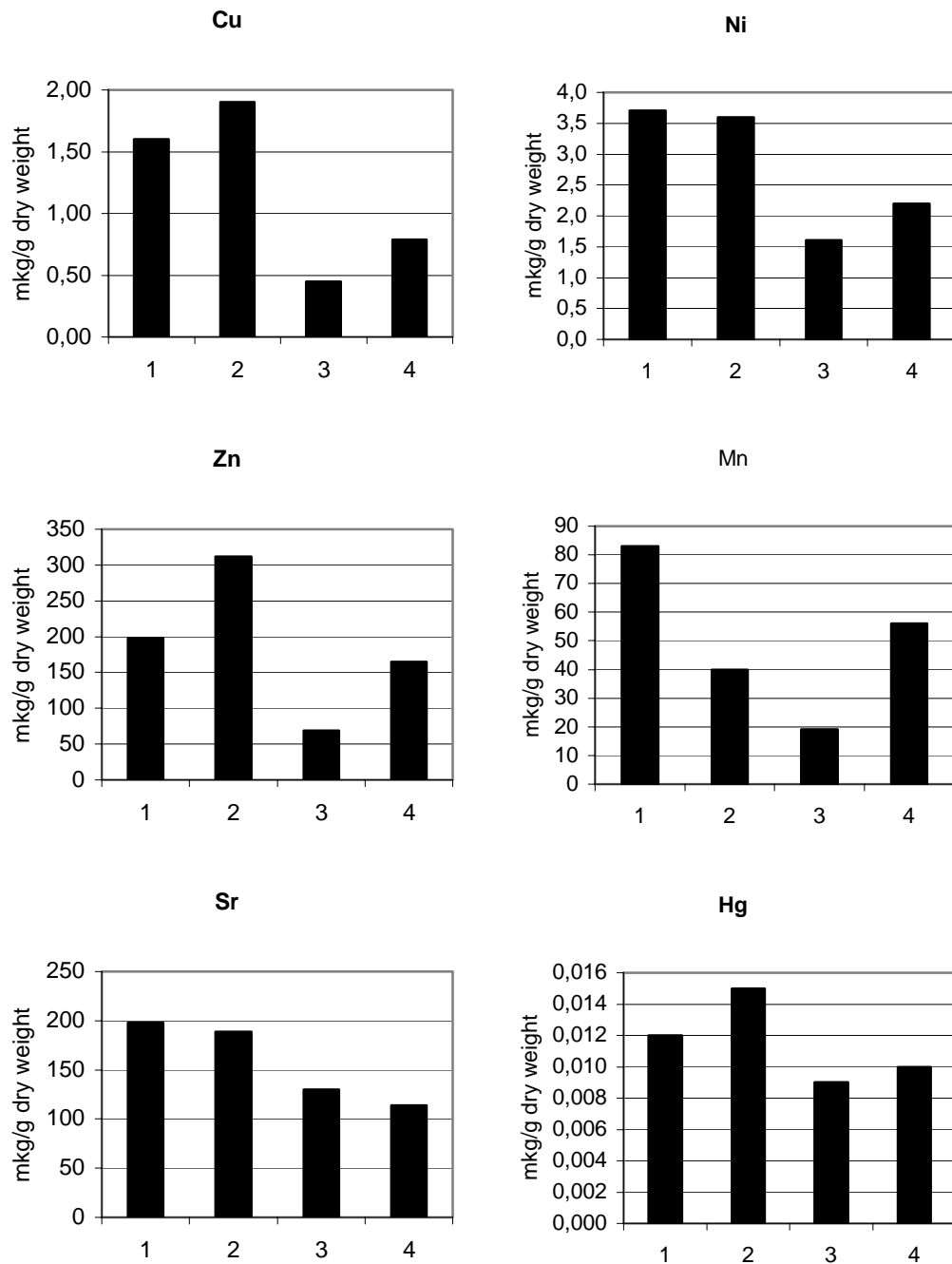

Figure 3.3. Heavy metal concentrations in kidneys of fish of the Kuetsjarvi Lake in 2004 (1 – sparsely rakered whitefish, 2 – densely rakered whitefish, 3- perch, 4 - pike).

Gills. No essential differences in copper concentrations between two forms of whitefish were revealed. It was found out, that the content of copper in perch and pike was twice as lower that in whitefish. The same was established for Ni. The highest mean concentrations of zinc were registered in pike - 511 $\mu kg/g^{-1}$ dry wt, the lowest ones – in perch: 70 $\mu kg/g^{-1}$ dry wt. No difference was found between the whitefish. Manganese accumulated in abundance in whitefish and pike. the inter-species differences were negligible as regards strontium content. The mercury data analysis indicated not very sharp, as in other organs, difference in its accumulation between the s.r. whitefish and predatory fish. The Hg concentrations in d.r. whitefish were twice as higher as in other species (*Figure 3.4*).

Figure 3.4. Heavy metal concentrations in gills of fish of the Kuetsjarvi Lake in 2004 (1 – sparsely rakered whitefish, 2 – densely rakered whitefish, 3- perch, 4 - pike).

Skeleton. All metals accumulate in higher quantities in whitefish. The differences between the whitefish vary from 2 to 4 times. Perch had minimum metal concentrations more often that other species. Except for zinc and manganese, no adequate differences were revealed in metal accumulation between the s.r. and d.r. whitefish (*Figure 3.5*).

Figure 3.5. Heavy metal concentrations in skeleton of fish of the Kuetsjarvi Lake in 2004 (1 – sparsely rakered whitefish, 2 – densely rakered whitefish, 3- perch, 4 - pike).

Appendix 4. Detailed presentation of heavy metal contaminations in fish from Skrukkebukta

Muscle. Cu concentrations in muscle didn't differ much between the species. The highest mean concentrations were registered in 2002 in pike – 0.84 μkg/g^{-1} dry weight. The highest mean concentrations in 2004 were found in perch. Ni accumulated most actively in muscle of d.r. whitefish, the maximum and minimum concentrations (pike) differed by a factor of two. Zinc contamination of d.r. whitefish, pike and perch kept at a constant level, the index of s.r. whitefish being twice as lower. The Mn concentrations increased from 2002 to 2004 in s.r. whitefish and decreased in pike. Perch had minimum mean concentrations. Perch also had minimum strontium concentrations. But as regards mercury, perch showed the ability of intensive bioaccumulation and mean concentration was 0.78 μkg/g^{-1} dry weight (*Figure 4.1*).
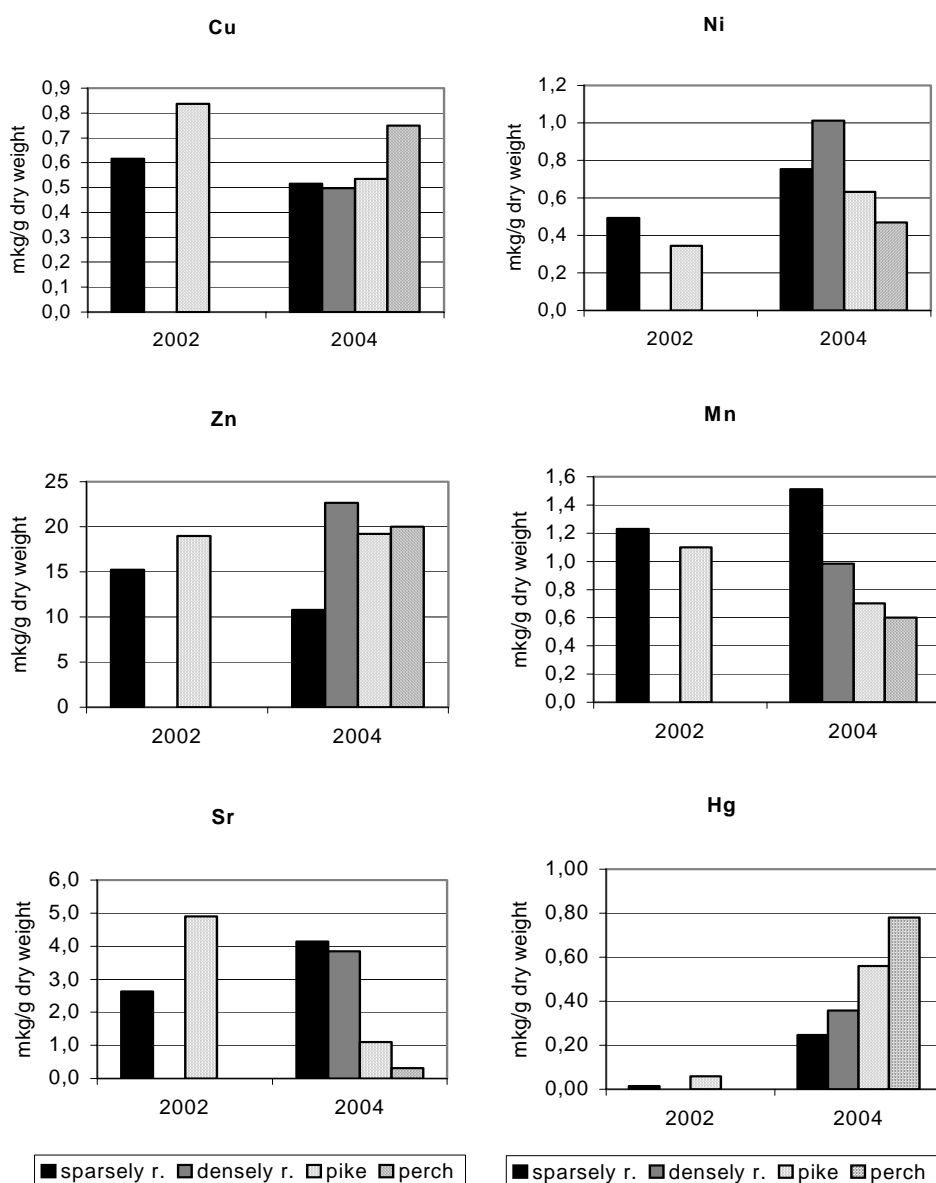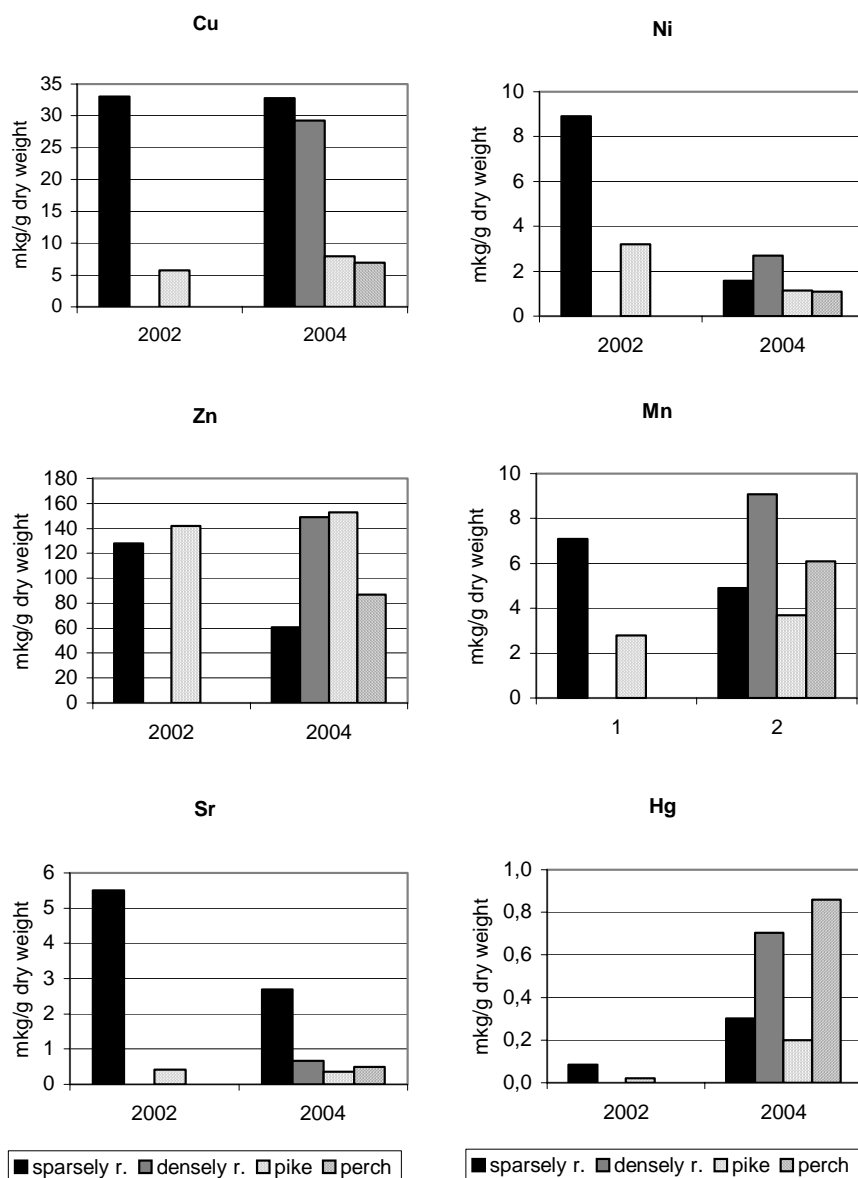

Figure 4.1. Heavy metal concentrations in muscle of fish of the location Skrukkebukta in 2002 2004 (1 – sparsely rakered whitefish, 2 – densely rakered whitefish, 3- pike, 4 - perch).

Liver. Cu contaminations of whitefish and pike remained practically constant throughout the whole study period. No differences were revealed between s.r. and d.r. whitefish and between pike and whitefish. At the same time the mean Cu concentrations of predatory species were 4 times lower than of benthic-feeding and plankton-feeding fish. The abrupt nickel reduction was observed in liver of the fish caught in 2004 as compared to the data of 2002. As before the predatory species are characterized by the reduced level of Ni accumulation. Zn accumulated in large amounts in liver of d.r. whitefish and pike. The interannual comparison revealed that s.r. whitefish was characterized by a twofold reduction of mean Zn concentrations; the index of pike remained unchanged. The Mn accumulation rate was the same. Strontium concentrations in liver of s.r. whitefish were adequately higher in both study periods than in liver of d.r. whitefish, pike and perch. The capacity for mercury accumulation of s.r. whitefish was lower than of d.r. whitefish and perch. Maximum Hg concentrations were typical of perch and amounted to 0.86 μkg/g^{-1} dry weight (*Figure 4.2*).
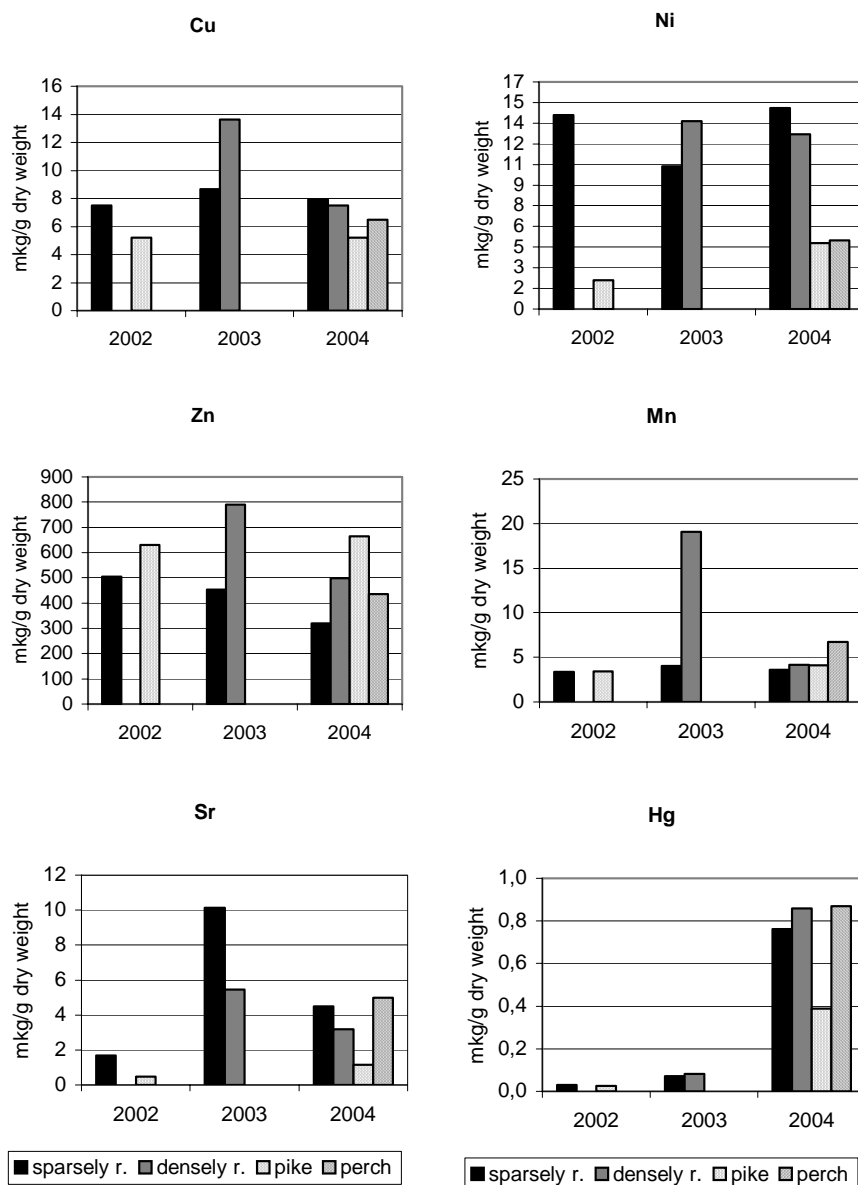

Figure 4.2. Heavy metal concentrations in liver of fish of the location Skrukkebukta in 2002 2004 (1 – sparsely rakered whitefish, 2 – densely rakered whitefish, 3- pike, 4 - perch).

Kidney. The copper concentrations varied insignificantly in all examined species from 5.2 to 8.7 μkg/g^{-1} dry weight throughout the whole study period. Ni also had low annual variability and adequately low concentrations in predatory species – trout, pike and perch. The annual variability rate of Zn concentrations revealed a tendency to small variability for s.r. whitefish. No connection was found out between the trophic status of the fish and the Zn accumulation level. The same relates to manganese. Sr concentrations in liver of both forms of whitefish, trout and perch were several times higher than in liver of pike. In 2002 mean Sr concentrations in liver of fish was lower than in subsequent years of study. The level of mercury concentrations in 2002 didn't adequately differ in s.r. whitefish and pike. In 2004 the mercury concentrations rose sharply. The highest values were observed for perch and d.r. whitefish (*Figure 4.3*).

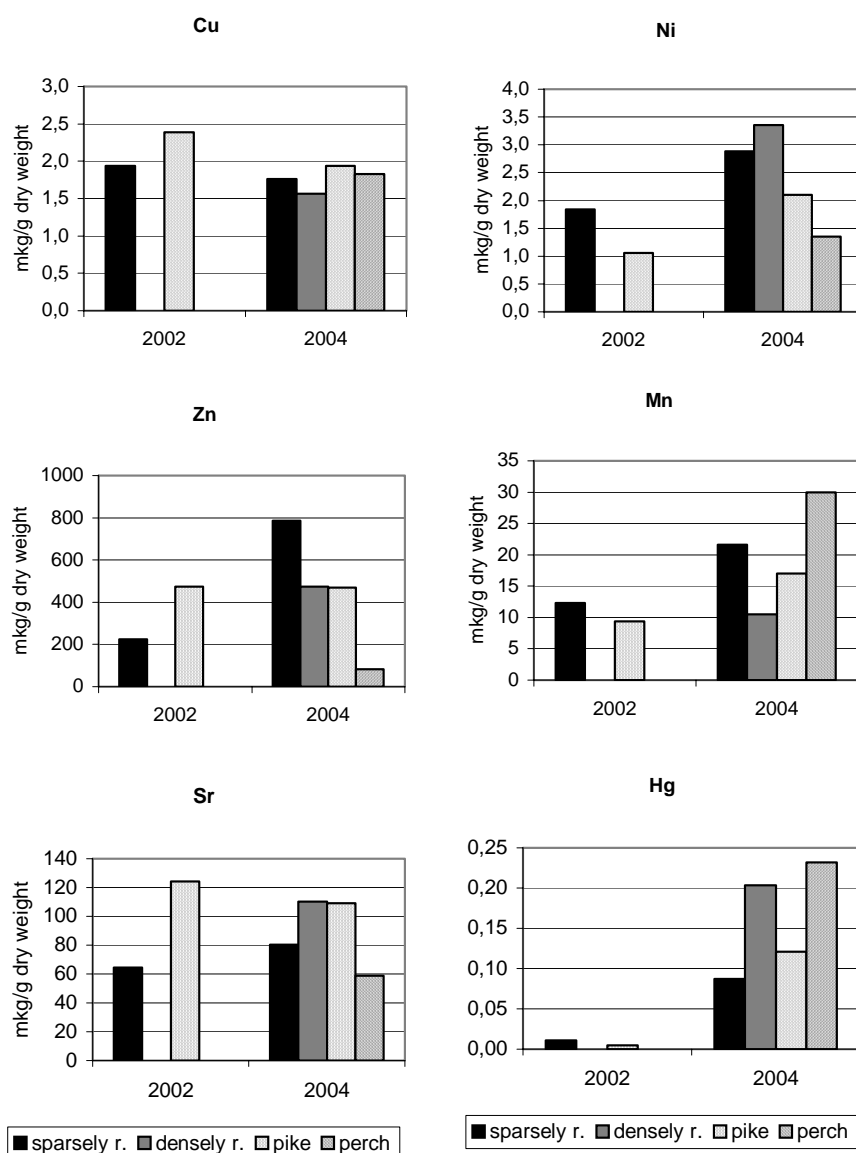Figure 4.3. Heavy metal concentrations in kidneys of fish of the location Skrukkebukta in 2002 2004 (1 – sparsely rakered whitefish, 2 – densely rakered whitefish, 3- pike, 4 - perch).

Gills. No adequate differences in copper concentrations between the whitefish, pike and perch were detected in 2002 and 2004. The highest values of Ni concentrations were registered for whitefish, the index increased sharply if to compare the data of 2002 and 2004. The comparison of mean Zn concentraions revealed its greater variability in various species. Maximum mean Zn concentration was found in s.r. whitefish and minimum – in perch. The data on manganese contamination in 2004 indicate that the highest values were registered for perch, being three times higher than for d.r. whitefish. In 2004 high strontium concentrations were typical of d.r. whitefish and pike - over 100 μkg/g^{-1} dry weight, this being twice as higher than in gills of perch. The comparison of data for 2002 and 2004 indicates, that the same as in other organs, the abrupt growth of mercury concentrations in gills. It would hold for all the species (*Figure 4.4).*
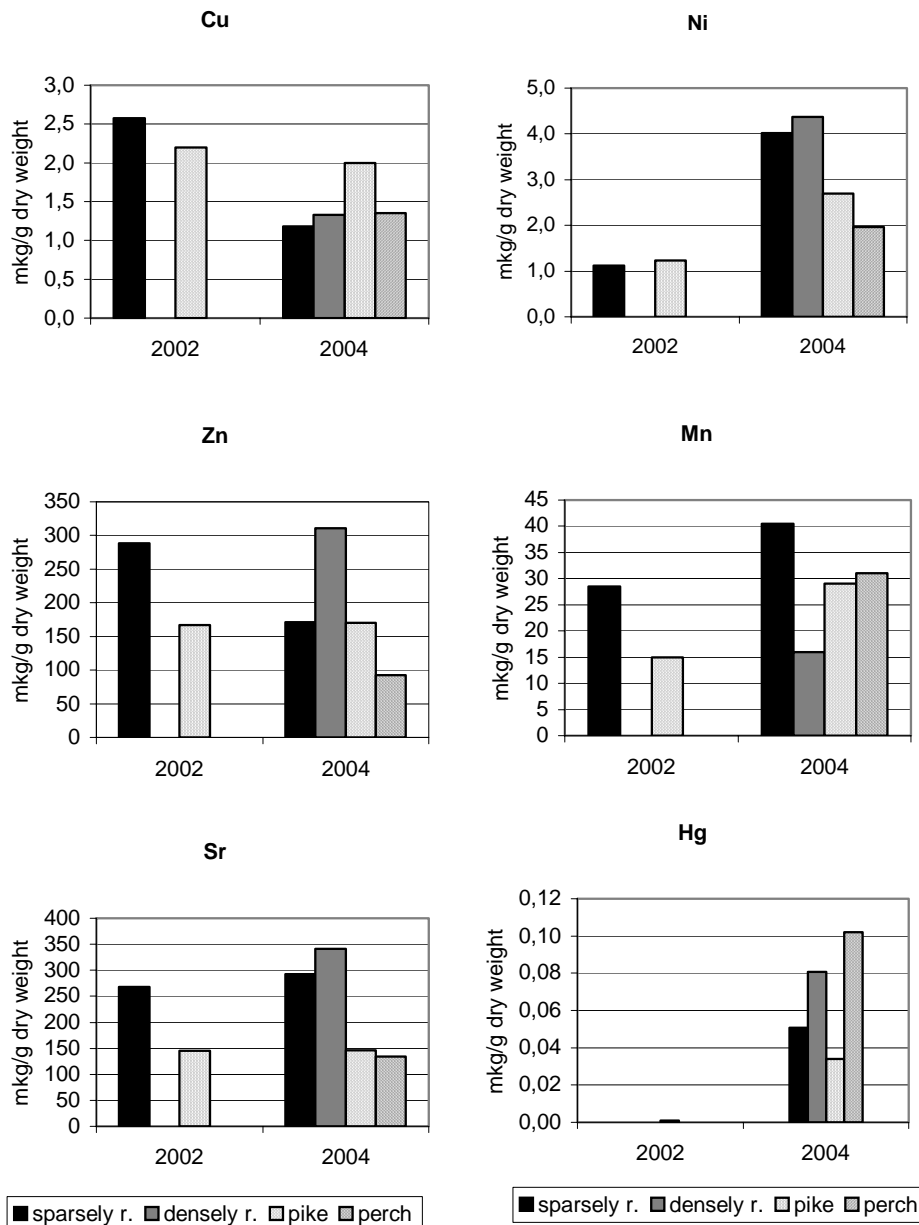

Figure 4.4. Heavy metal concentrations in gills of fish of the location Skrukkebukta in 2002 2004 (1 – sparsely rakered whitefish, 2 – densely rakered whitefish, 3- pike, 4 - perch).

Skeleton. It was established, that copper, zinc and manganese concentrations decreased in s.r. whitefish in the period from 2002 to 2004. No annual dynamics of these elements was found in pike, except for manganese: its concentrations increased twofold. The growth of Ni concentrations was revealed for both species. Inter-species comparison showed a slight tendency of Ni concentrations to decrease if to pass from the whitefish to pike and to the perch. The lowest Zn and Sr concentrations were observed for the perch, though inter-species differences in strontium contaminations are not strongly pronounced. As in all organs considered earlier, perch ranks first in the ability for mercury bioaccumulation in skeleton (*Figure 4.5*).

Figure 4.5. Heavy metal concentrations in skeleton of fish of the location Skrukkebukta in 2002 2004 (1 – sparsely rakered whitefish, 2 – densely rakered whitefish, 3- pike, 4 - perch).

Appendix 5. Detailed presentation of heavy metal contaminations in fish from Vaggatem

Muscle. Cu concentration in muscle of sparsely rakered whitefish was a little higher than of densely rakered whitefish, pike and perch. The comparison of data for two study periods showed that this index of d.r. whitefish rose and the index of s.r. whitefish fell and the index of pike remained the same. Ni concentrations of both forms of whitefish didn't show much difference in 2002 and were twice as higher as Ni concentrations in pike. In 2004 The Ni contamination of whitefish reduced from 1-1.2 to 0.6-0.8 $\mu kg/g^{-1}$ dry weight but Ni contamination of pike increased in two times. Ni concentrations in perch were comparable to that of the d.r. whitefish. D.r. whitefish was characterized by the highest Zn concentrations in 2002. In 2004 this index of d.r. whitefish decreased in two times and became a minimum as compared to the other studied species. Zn contamination of pike and s.r. whitefish increased. Perch occupies intermediate position as regards Zn accumulation. The Mn distribution pattern in the same as that of the Zn. In 2002 maximum Sr contamination was registered in pike. On average, C_{Sr} in muscles exceeded 5 $\mu kg/g^{-1}$ dry weight. In 2004 the level of strontium accumulation decreased in 2.4 times. Sr contamination of whitefish changed slightly. Perch was characterized by minimum values. Though in 2004 the perch took the first place in mercury bioaccumulation, the pike ranked next (*Figure 5.1*).
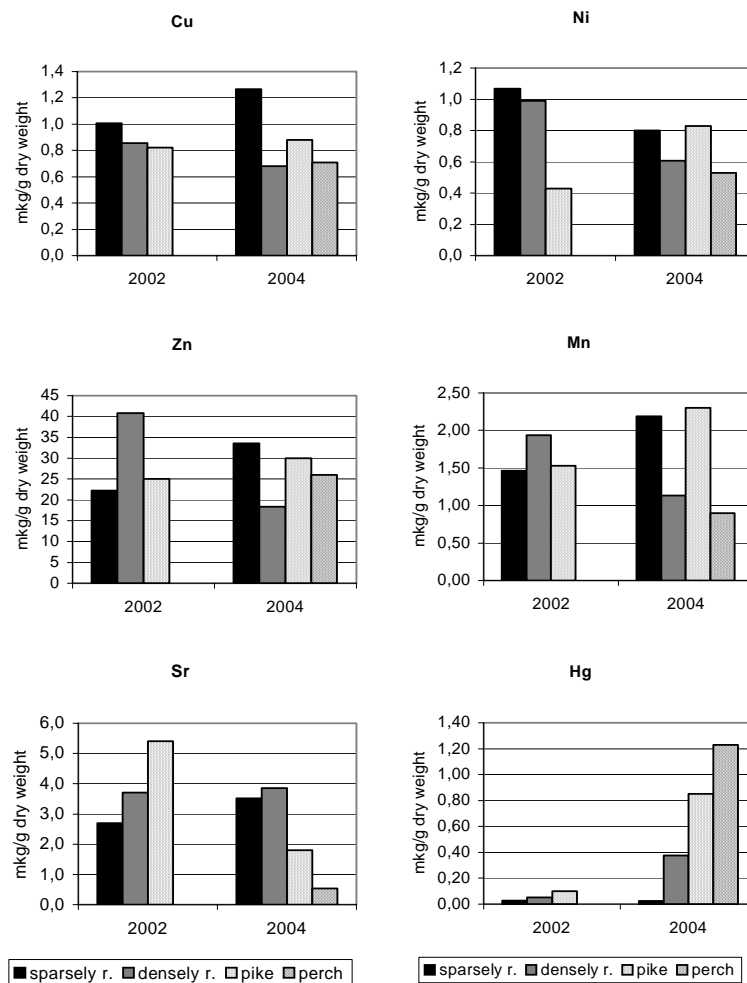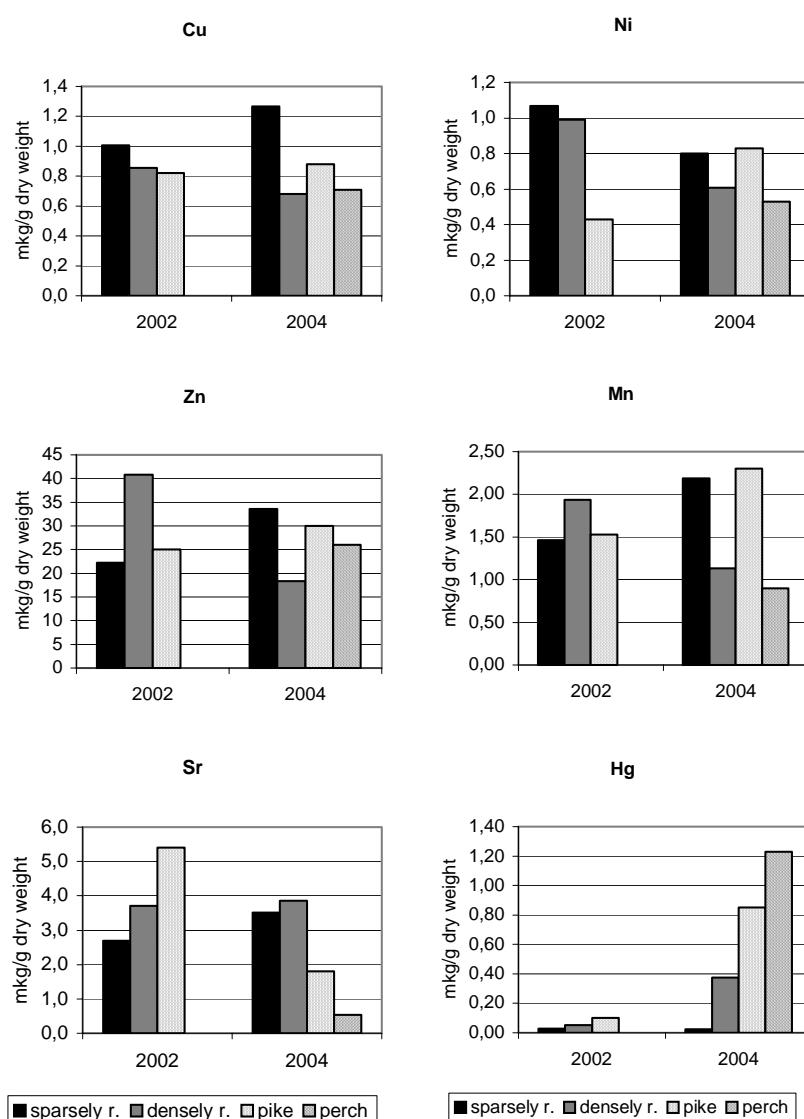

Figure 5.1. Heavy metal concentrations in muscle of fish of the location Vaggatem in 2002 2004 (1 – sparsely rakered whitefish, 2 – densely rakered whitefish, 3- pike, 4 - perch).

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Liver. Cu concentrations remained constant in the s.r whitefish and pike throughout the whole study period. Mean Cu concentrations n the d.r. whitefish increased in 2004. Minimum mean concentrations were characteristic of perch. The comparison of data of 2002 and 2004 showed that Ni contamination increased in all species. Comparison of species-specific Ni accumulations showed that the largest amounts of this element are accumulated in liver of d.r. whitefish. Zn concentrations in liver of fish in 2004 varied within small limits. In the previous period of studies the highest mean value was registered for pike. As regards manganese contamination the highest values were observed in pike, mean concentrations of whitefish and perch vary insignificantly: from 6 to 9 μkg/g^{-1} dry weight. In both periods the liver of whitefish was contaminated stronger than that of pike and perch. A considerable rise in mercury concentrations was observed in 2004 for d.r whitefish and pike. Mean concentrations in 2002 and 2004 differed by a factor of four. The maximum levels were determined for perch and d.r. whitefish.
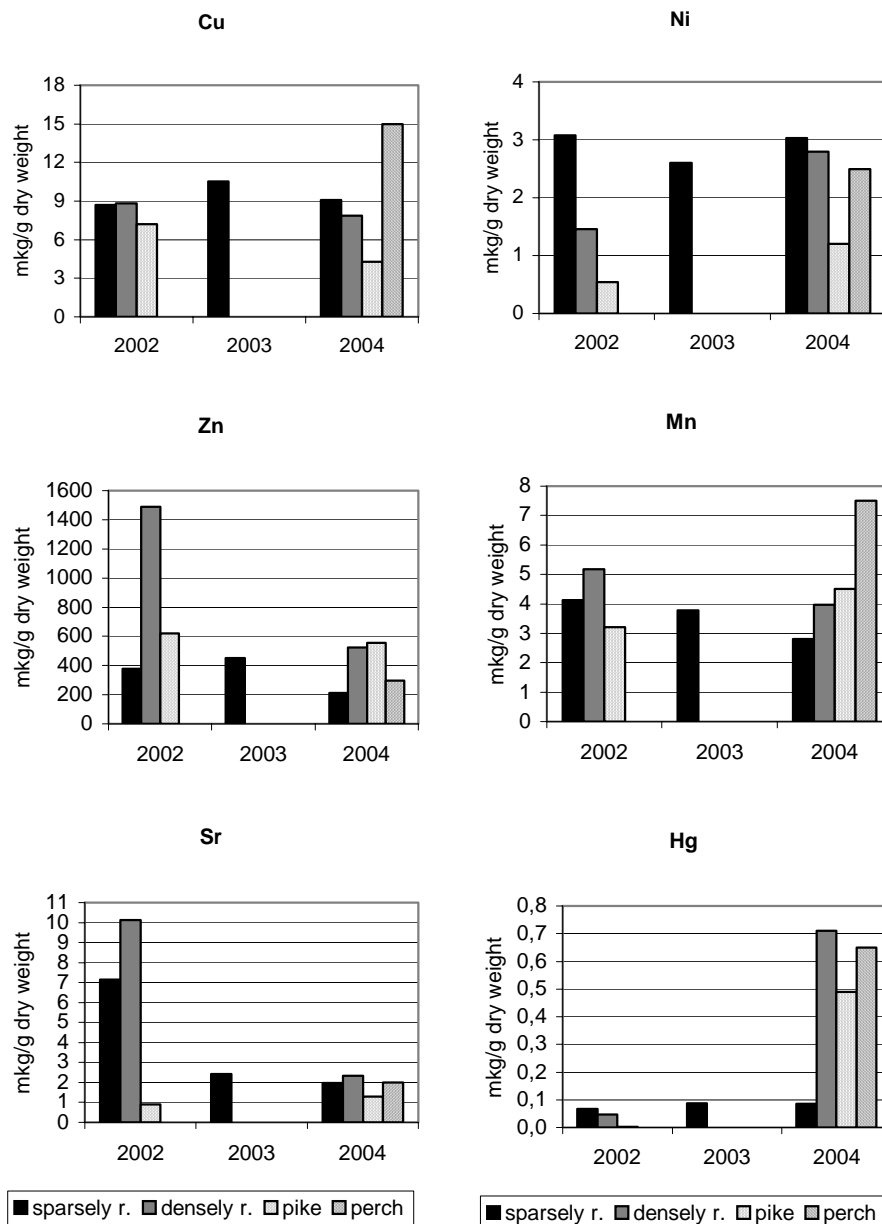

Figure 5.2. Heavy metal concentrations in liver of fish of the location Vaggatem in 2002 2004 (1 – sparsely rakered whitefish, 2 – densely rakered whitefish, 3- pike, 4 - perch).

Kidney. Throughout the whole study period the copper concentrations in kidney of whitefish varied within small limits from 7.9 to 10.6 $\mu kg/g^{-1}$ dry weight. In some individual fish C_{Ni} reached 19 and 170 $\mu kg/g^{-1}$ dry weight. The comparison of data for two periods indicates that Zn concentrations in kidney of all types of fish decreased in 2004. At the same time the minimum concentrations are characteristic of s.r. whitefish. Mn contamination also has a slight downward trend for whitefish and an upward trend for pike. The highest mean values were found in perch. Sr concentrations in kidney of both forms of whitefish and perch were several times higher than that of pike. A similar tendency remains in both years. Mercury concentrations in 2002 in all three species don't differ for certain. In 2004 the d.r. whitefish and pike had C_{Hg} of the higher order. The same high values were registered for the perch (*Figure 5.3*).
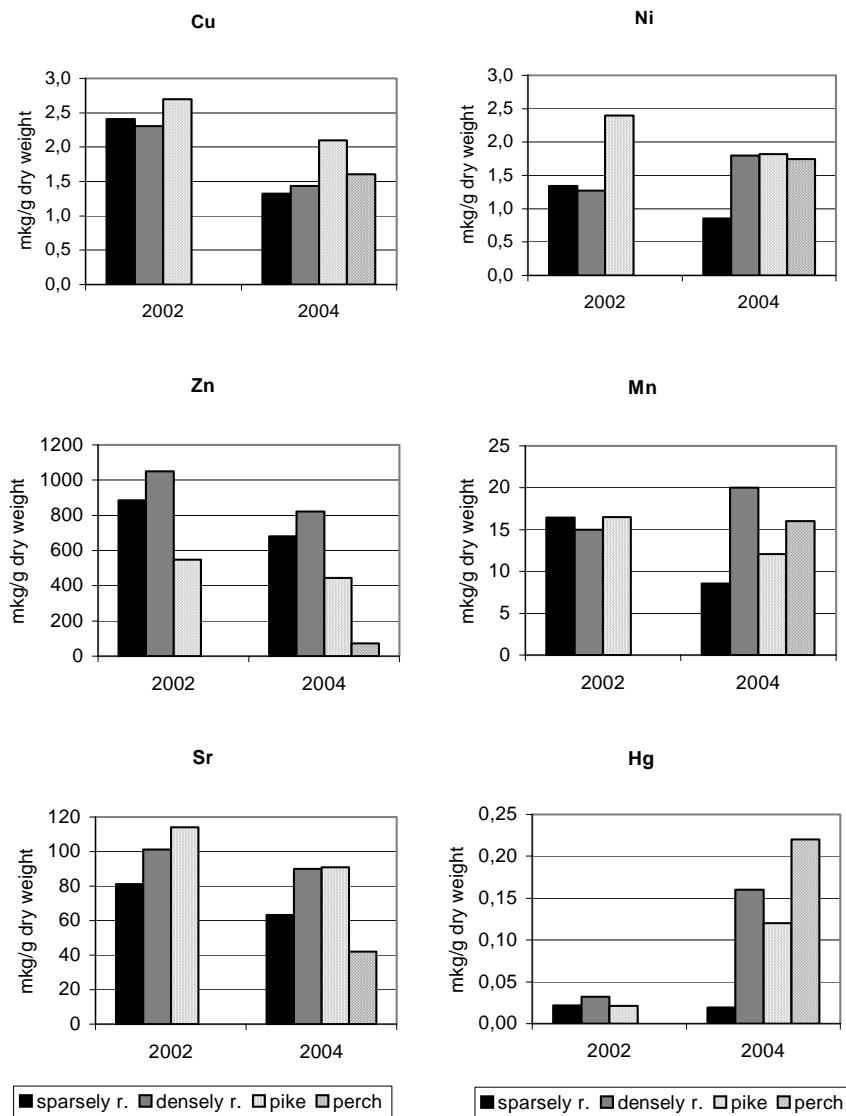

Figure 5.3. Heavy metal concentrations in kidneys of fish of the location Vaggatem in 2002-2004 (1 – sparsely rakered whitefish, 2 – densely rakered whitefish, 3- pike, 4 - perch).

Gills.

No significant differences in Cu concentrations between the whitefish, pike and perch were detected in 2002 and 2004, but a decrease tendency was discovered in 2004 in mean concentrations of this element in all species. Data analysis for 2002 showed that pike has the highest Ni concentrations. In 2004 only Ni concentrations in s.r. whitefish decreased compared to 2002 and to the other fish species. The comparison of mean values of Zn accumulation revealed the next distribution pattern in ascending order: perch<<pike<<s.r. whitefish<< d.r. whitefish. No apparent inter-species differences in Mn concentrations were discovered in 2002. In 2004 the minimum mean concentrations were found in s.r. whitefish and the maximum values - in perch.

High strontium concentrations were typical of pike. Though the difference form d.r whitefish was not established. The minimum values were registered for the perch. Data analysis on mercury accumulation showed that all species except for the s.r. whitefish have a considerable growth in mercury accumulation in 2004, in comparison with 2002. Perch dominated in mercury contaminations (*Figure 5.4*).
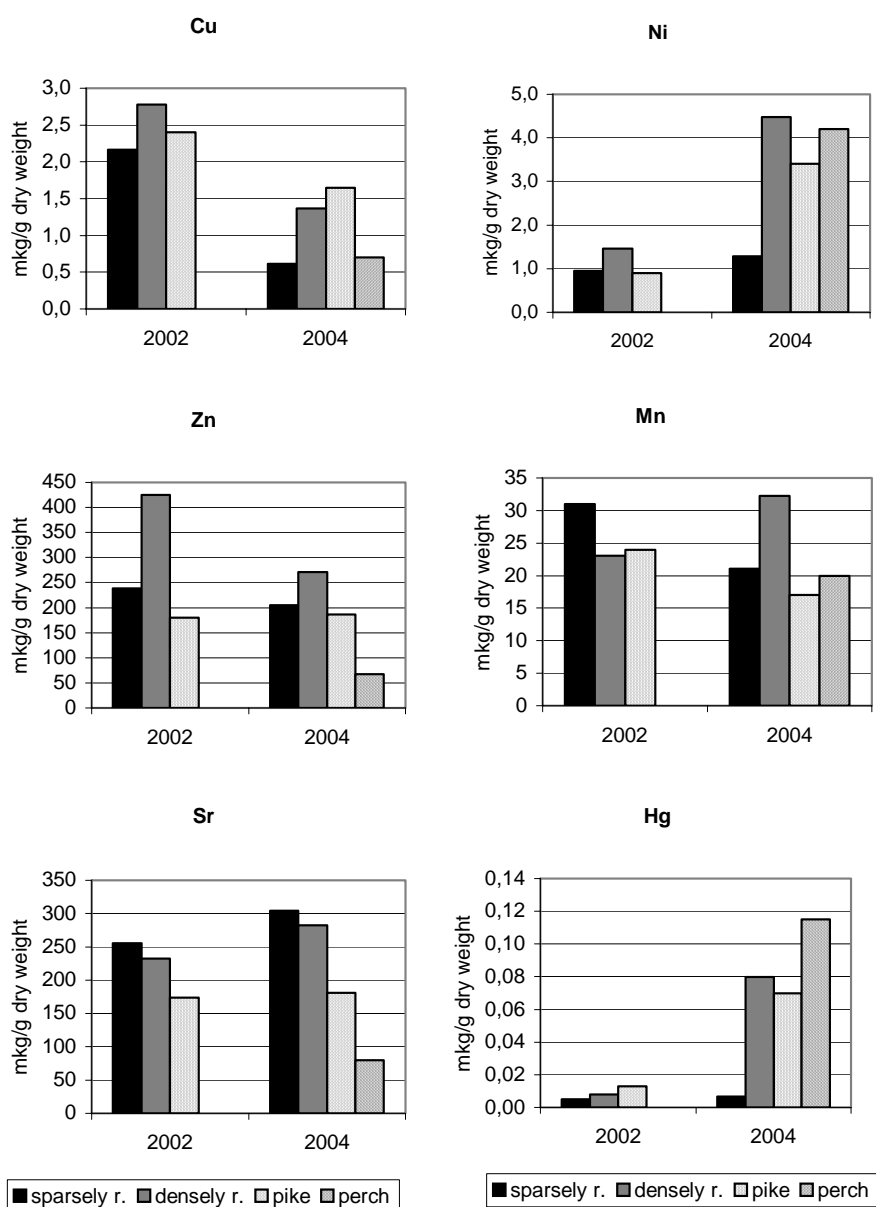

Figure 5.4. Heavy metal concentrations in gills of fish of the location Vaggatem in 2002 2004 (1 – sparsely rakered whitefish, 2 – densely rakered whitefish, 3- pike, 4 - perch).

Skeleton. It was found out, that in 2004 the mean copper concentrations decreased in the skeleton of all species under study. At the same time the minimum values were observed in the s.r. whitefish throughout all years of study. As regards Ni an inverse tendency was revealed and the level of its accumulation increased. As before the minimum values were typical of the s.r. whitefish. Zn concentrations varied within small limits and interspecies differences slightly manifest themselves. The perch became an exception, as Zn concentrations in its skeleton were lower than in the other species. Mn concentrations in both years were almost equal in all species under study and failed to reveal any inter-yearly differences. The same is typical of the strontium accumulation. As in all earlier considered organs a rapid growth of mercury accumulation in skeleton of d.r. whitefish and pike was detected (*Figure 5.5*).

Figure 5.5. Heavy metal concentrations in skeleton of fish of the location Vaggatem in 2002 2004 (1 – sparsely rakered whitefish, 2 – densely rakered whitefish, 3- pike, 4 - perch).

Appendix 6. Detailed presentation of heavy metal contaminations in fish from Rajakoski

Muscle. Cu concentrations in muscle of s.r. whitefish were lower than in muscle of pike. The comparison of data for two study periods showed that this index remained constant in both species. Ni concentrations in 2002 in whitefish and pike didn't adequately differ. In 2004 the Ni contamination level of whitefish according to weighted mean values didn't change and was equal to 0.57 μkg/g $^{-1}$ dry wt, in some samples the C_{Ni} was 16.8 μkg/g $^{-1}$ dry wt. The highest Zn concentrations in 2002 were observed in pike. In 2004 the index remained the same. Zn concentrations in pike and s.r. whitefish increased. Perch occupies intermediate position in Zn accumulation. The analysis of Mn distribution revealed the same pattern that was for Zn: uncertain increase of Mn in pike and absence of the annual dynamics. In 2002 the maximum Sr concentrations were registered for pike, being twice as higher than in whitefish. On average C_{Sr} varied in muscle f fish from 2.5 to 4.5 μkg/g $^{-1}$ dry wt, the index of perch being one order lower. The predatory fish species pike and perch are more predisposed to bioaccumulation of mercury. The level of mercury accumulation in these species is 5-6 times higher than in whitefish *(Figure 6.1)*.
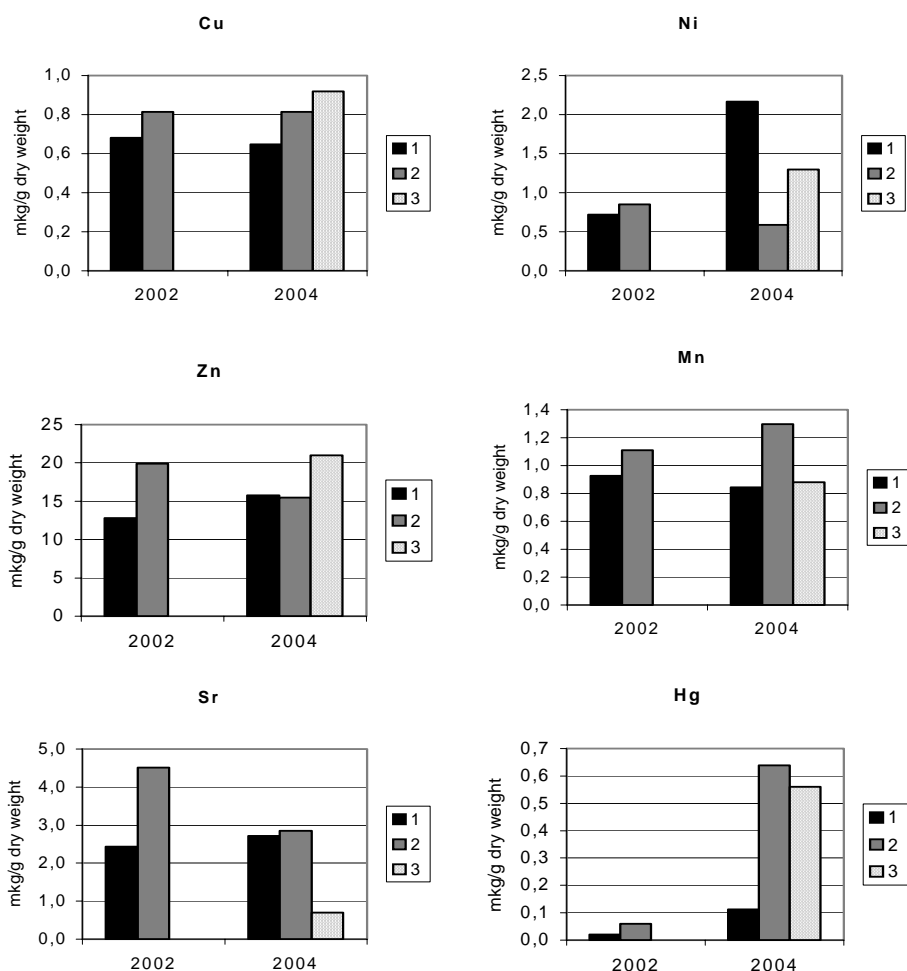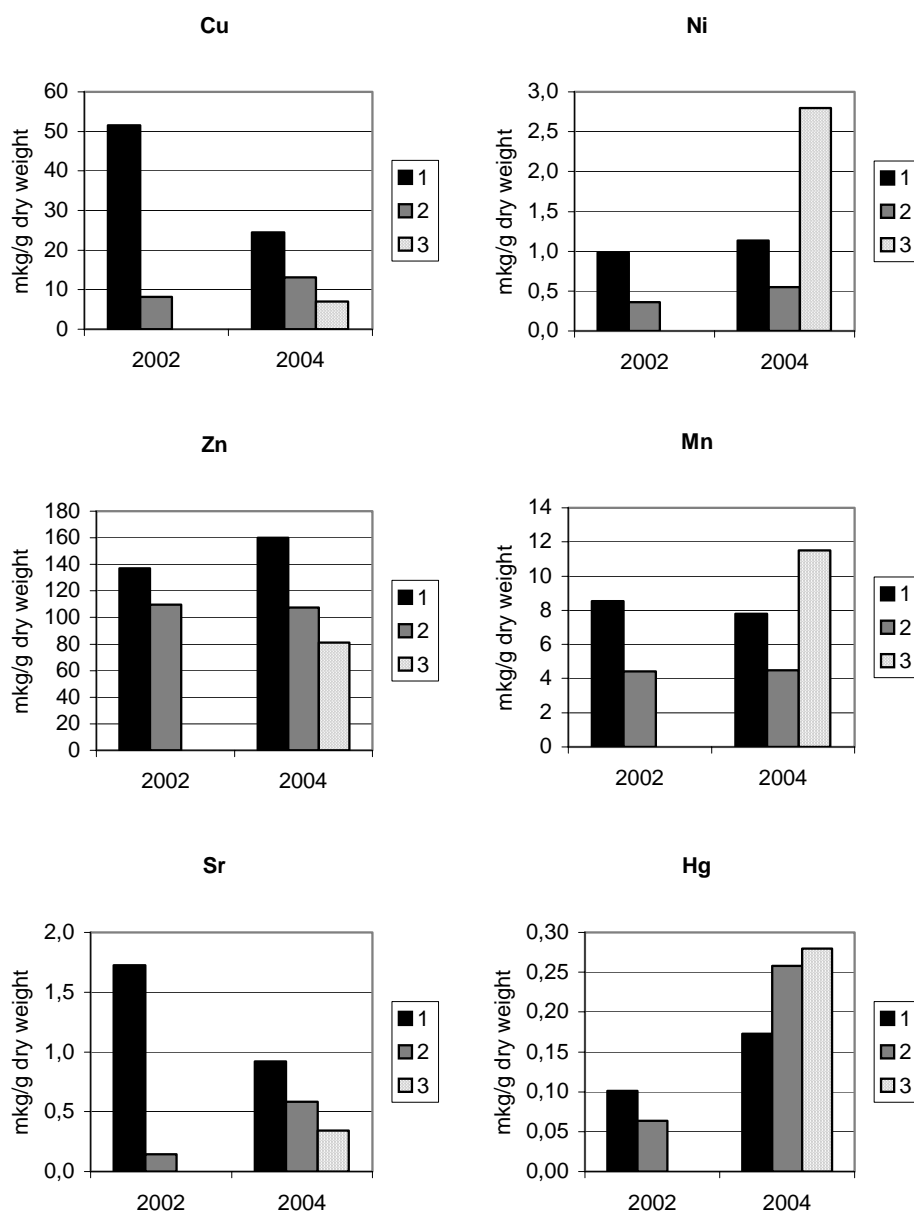

Figure.6.1. Heavy metal concentrations in muscle of fish of the lake Rajakoski location in 2002 2004 (1 – sparsely rakered whitefish, 2 – pike, 3- perch).

<u>Liver</u>. Cu concentrations in s.r. whitefish and pike remained practically unchanged throughout the whole study period. The Cu concentrations in predatory species were 2-3 times lower than in s.r. whitefish. Mean Cu concentration was 25 μkg/g $^{-1}$ dry wt, some samples had C_{Cu} equal to 130 μkg/g $^{-1}$ dry wt. The highest Ni concentrations were observed in s.r. whitefish, the concentrations in pike were twice as lower. No noticeable annual differences were observed as regards mean accumulation of Ni, Zn and Mn. The specific difference analysis showed that predatory fish tent to have lower concentrations of both these elements and Sr. Mercury had another distribution pattern in 2004 and maximum concentrations were found in perch and pike (*Figure 6.2*).

Figure 6.2 Heavy metal concentrations in liver of fish of the lake Rajakoski location in 2002 2004 (1 – sparsely rakered whitefish, 2 – pike, 3- perch).

<u>Kidney</u>. Throughout the whole study period Cu concentrations in kidney of whitefish and pike varied within small limits: from 8.6 to 11 μkg/g $^{-1}$ dry wt (whitefish) and from 4.2 to 5.8 μkg/g $^{-1}$ dry wt (pike). Minimum concentrations were typical of perch – 2.1 μkg/g $^{-1}$ dry wt. Ni contamination in kidney of whitefish was higher than in kidney of pike. A small difference was revealed between the pike and perch. One individual whitefish had C_{Ni} equal to 38 μkg/g $^{-1}$ dry wt. The comparison of data for two study periods showed that Zn concentrations in kidney of all species uncertainly increased in 2004. The growth of Zn content in pike was registered compared to whitefish. At the same time minimum concentrations were observed for perch. The similar trend was observed as regards Mn concentrations: uncertain annual differences and higher level of C_{Mn} in whitefish compared to pike. Sr concentrations in kidney of whitefish were several times higher than in kidney of pike and perch. The similar pattern holds true in both years of study. The level of mercury contamination of whitefish and pike in 2002 was adequately lower than in 2004 (*Figure 6.3*).
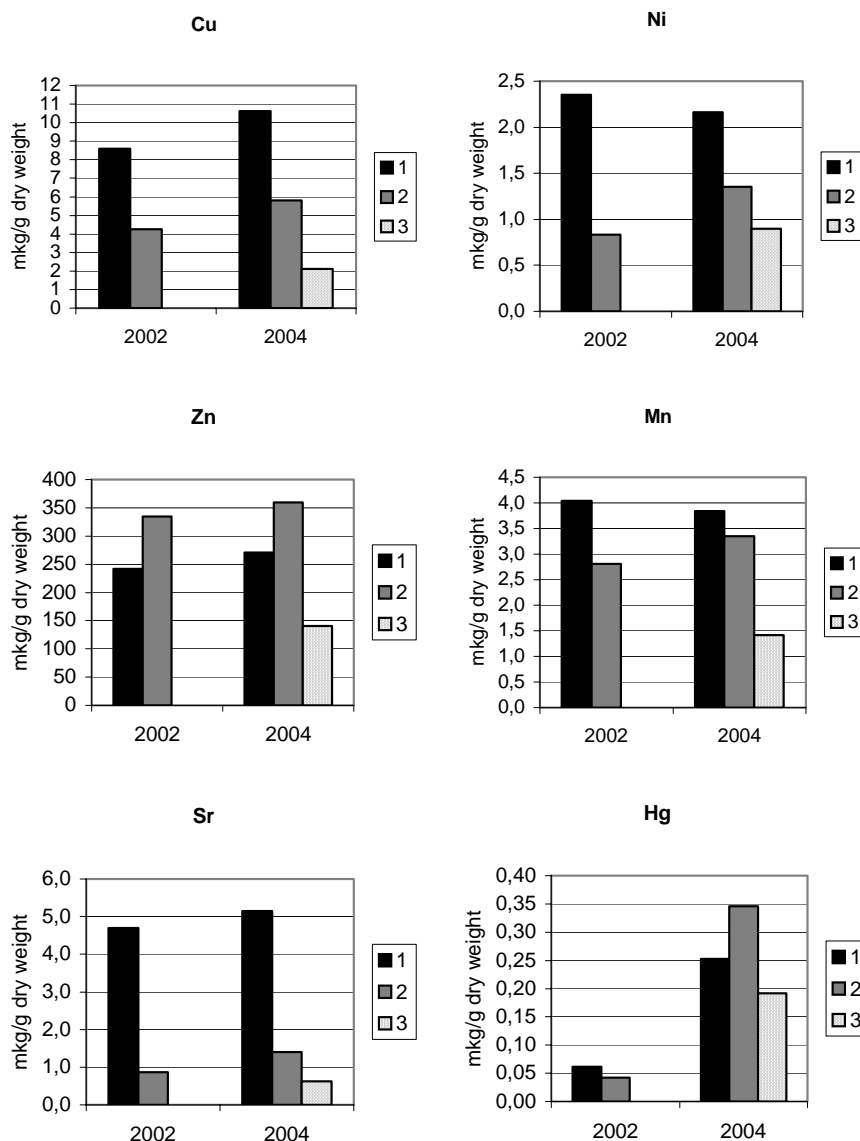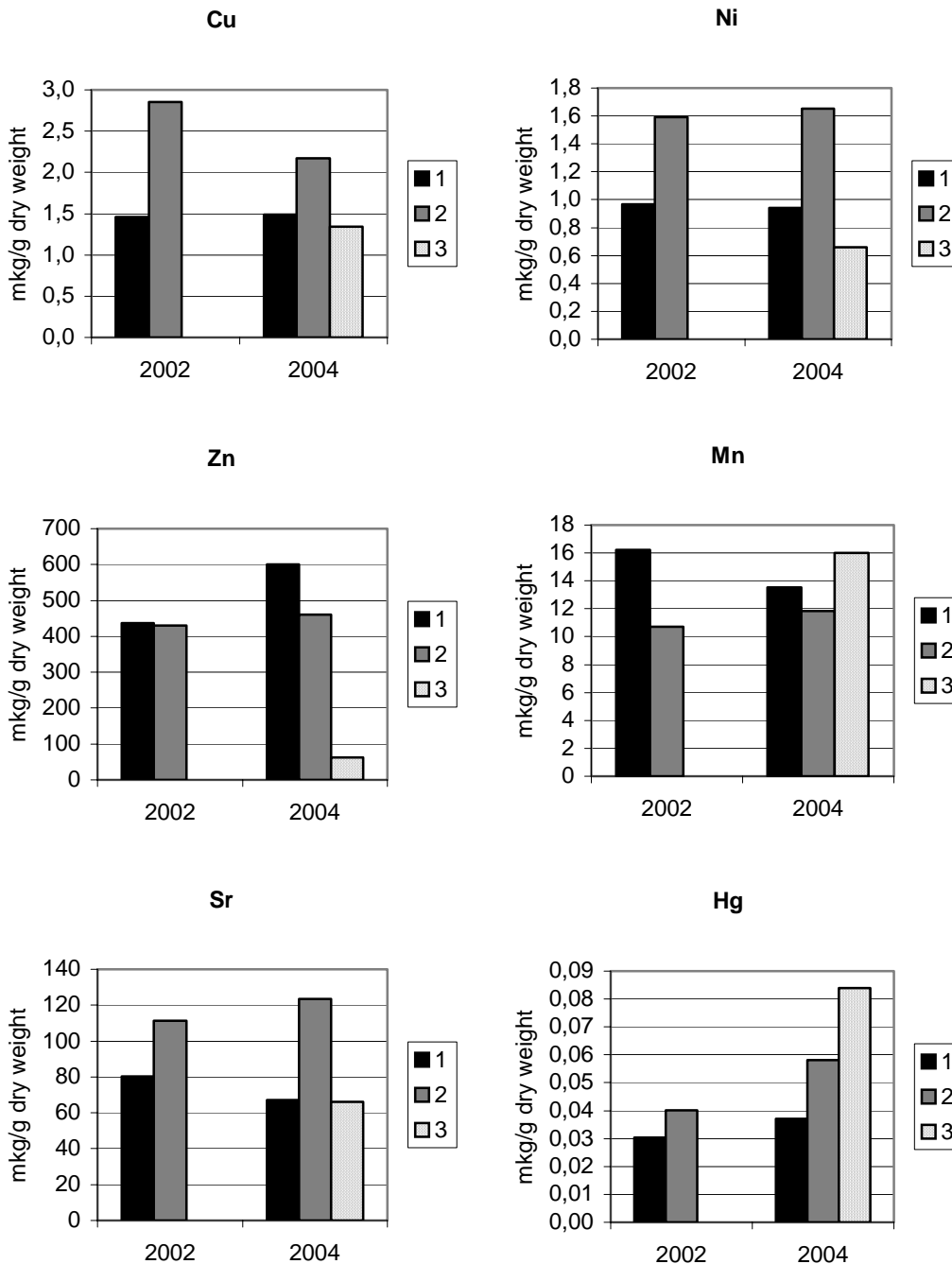

Figure 6.3. Heavy metal concentrations in kidneys of fish of the lake Rajakoski location in 2002 2004 (1 – sparsely rakered whitefish, 2 – pike, 3- perch).

Gills. No sensible differences in copper contamination of gills of whitefish, pike and perch were observed in 2004, but the decrease of mean level of Cu accumulation was registered for pike. The data analysis for two years of study showed that the highest values of Ni contamination were observed in pike. The same is true for nickel and strontium. Mean Zn concentrations were constant either in the light of inter-annual and inter-species comparison. High Sr concentrations were typical of pike, the Sr contaminations of perch and whitefish were equal. Mercury analysis data indicated not so sharp increase of its accumulation in 2004 and 2002 as in other water bodies. Perch dominates in mercury accumulation (*Figure 6.4*).
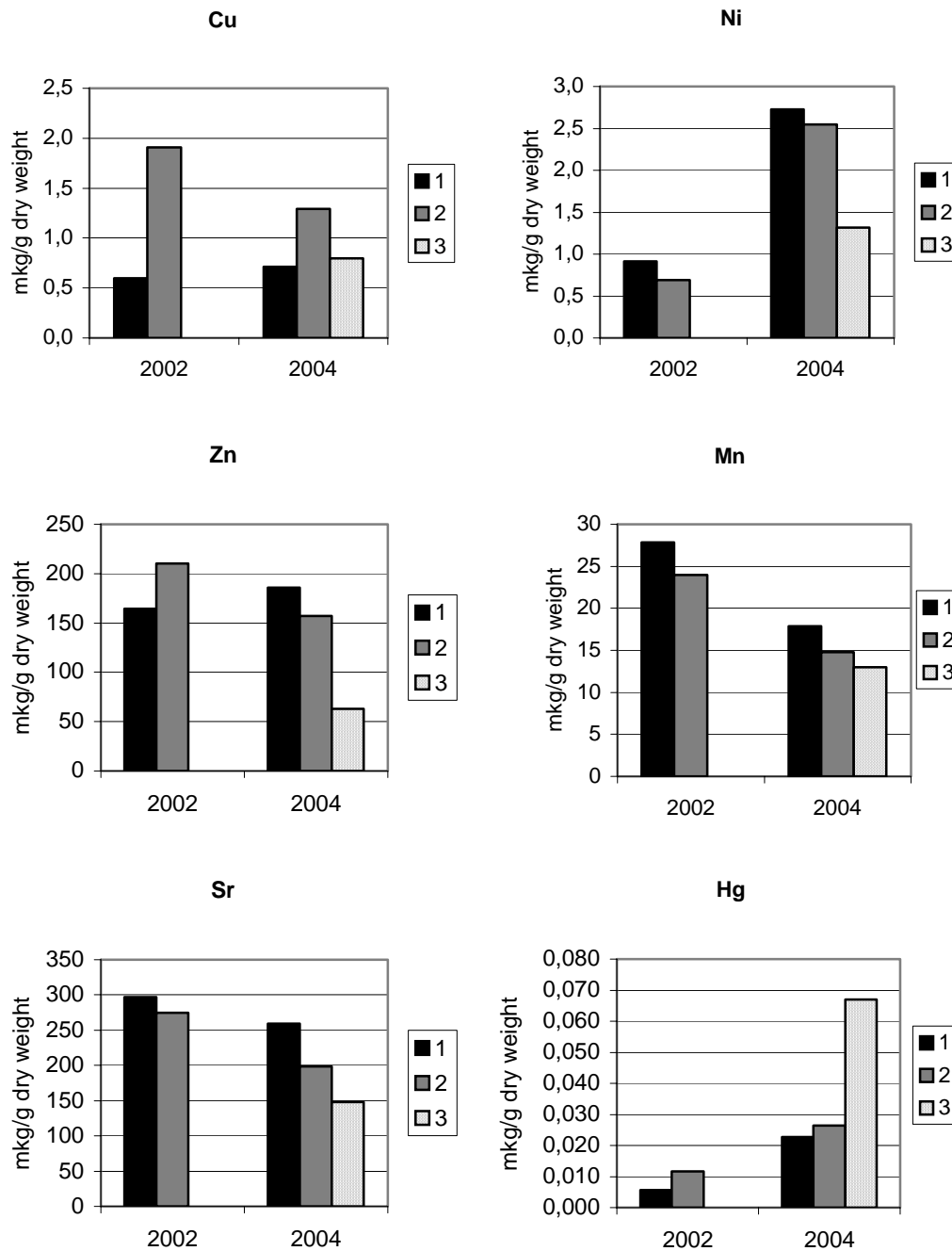

Figure 6.4. Heavy metal concentrations in gills of fish of the lake Rajakoski location in 2002 2004 (1 – sparsely rakered whitefish, 2 – pike, 3- perch).

<u>Skeleton</u>. Copper, zinc (2002) and mercury were the elements which concentrations were higher in pike. As regards Ni it was established that its concentrations in skeleton didn't have inter-species differences, but adequately increased in 2004. Zn concentrations didn't vary mach during the years of study; interspecies differences are poorly defined, except for the perch, which has lower mean C_{Zn}. Mn concentrations decreased in 2004. The same was observed for strontium. Hg concentrations in skeleton of all species increased abruptly in 2004. Maximum level was observed for the perch – 0.067 μkg/g $^{-1}$ dry wt. (*Figure 6.5*).

Figure 6.5. Heavy metal concentrations in skeleton of fish of the lake Rajakoski location in 2002 2004 (1 – sparsely rakered whitefish, 2 – pike, 3- perch).

Appendix 7. Detailed presentation of heavy metal contaminations in fish from Lake Inari

The following fish species were investigated for heavy metal contamination: whitefish (sparsely rakered and densely rakered), pike and trout. Due to the fact that only 1 and 2 samples of the trout and densely rakered whitefish were caught, they are not included into the description.

Muscle. The highest level of copper concentrations was registered in pike. The interspecies difference is negligible. The same was registered for nickel and zinc. The manganese concentrations in muscle of pike were twice as higher than in s.r. whitefish. The highest levels of strontium accumulation were observed in predatory species – pike (*Figure 7. 1*).
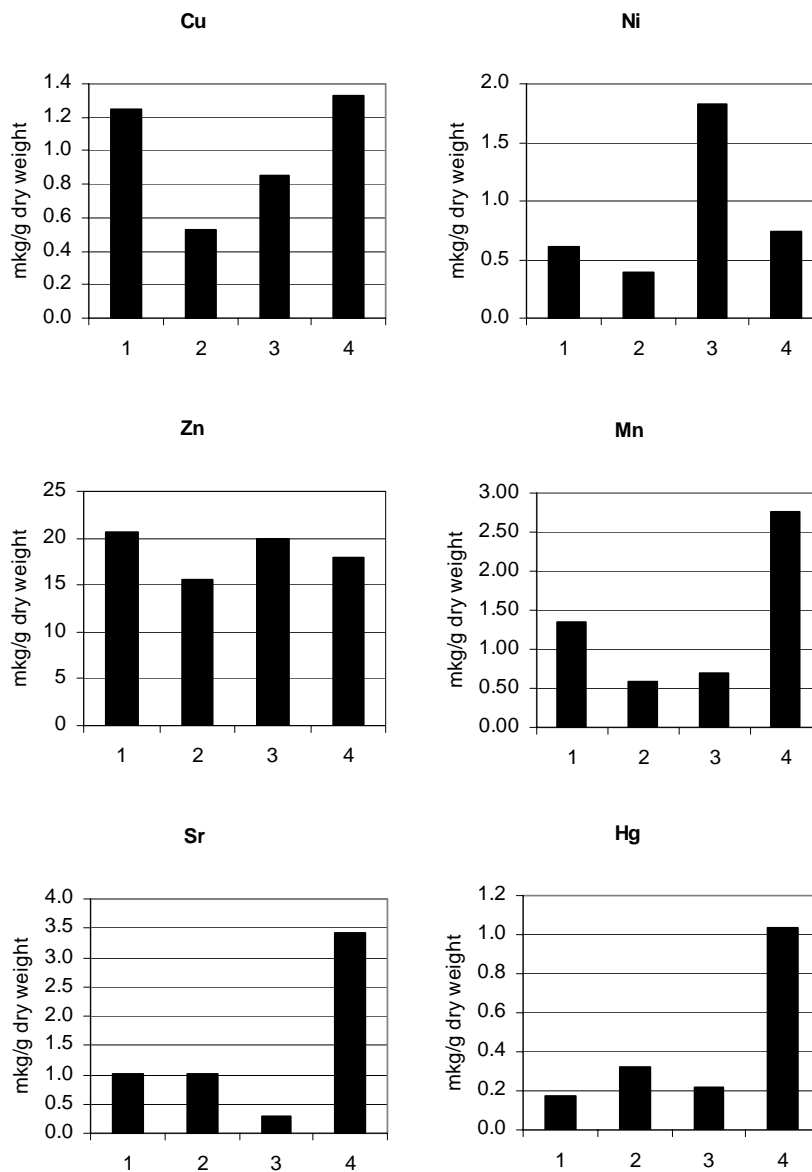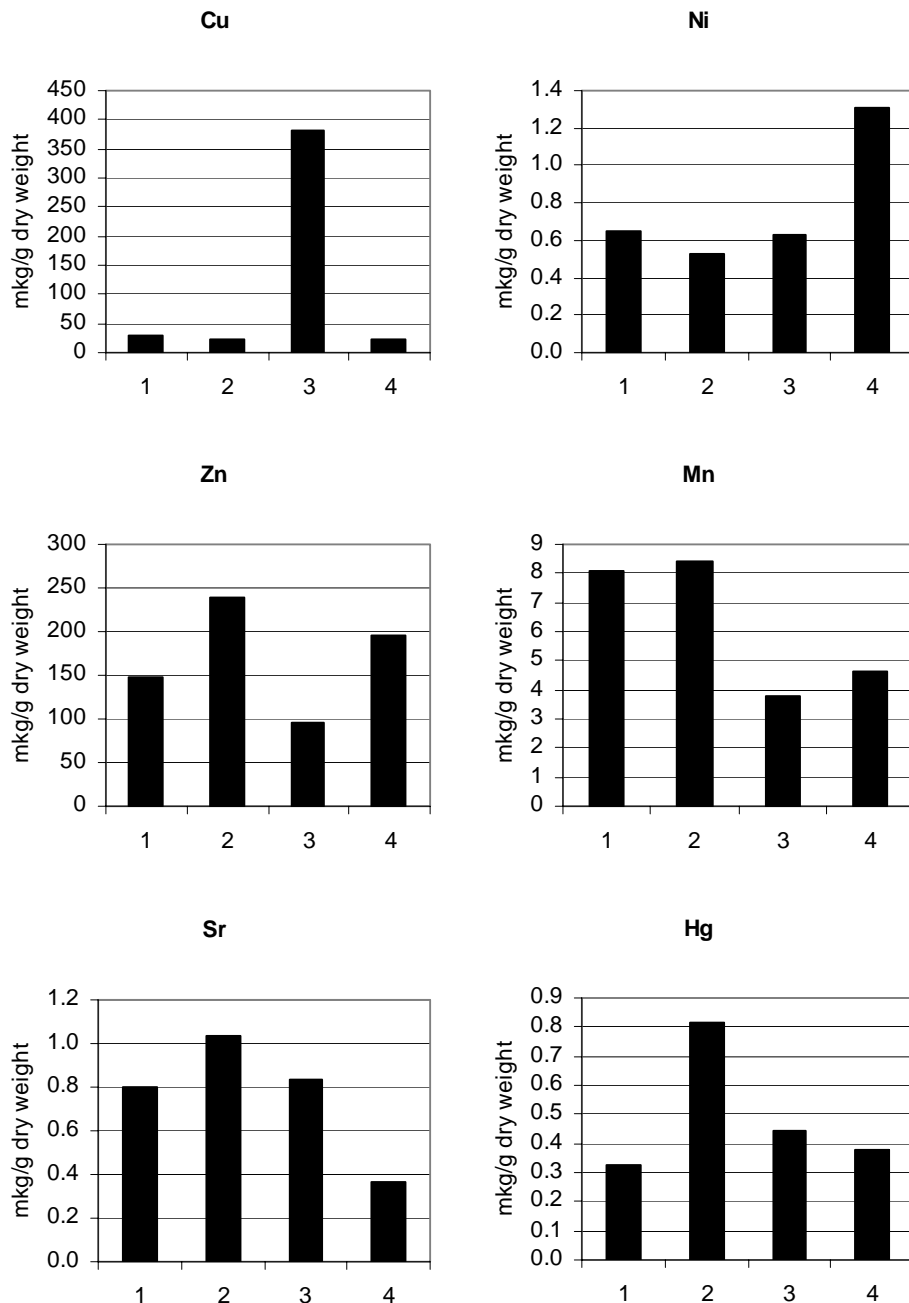

Figure 7.1. Heavy metal concentrations in muscle of fish of the Inari Lake in 2004 (1 – sparsely rakered whitefish, 2-densely rakered whitefish, 3-trout, 4-pike).

Liver. The copper concentrations in s.r. whitefish and pike don't differ adequately and were equal to 29 and 22 $\mu kg/g^{-1}$ dry wt respectively. Ni concentrations in pike were twice as higher than in whitefish. The maximum registered value for pike was 2.1 $\mu kg/g^{-1}$ dry wt. Mean zinc concentrations were higher in pike but a single sample of s.r. whitefish have maximum concentration of 510 $\mu kg/g^{-1}$ dry wt. Higher levels of manganese and strontium accumulation were observed in s.r. whitefish. Mean mercury concentrations in liver of whitefish and pike vary within small limits and were equal to 0.33 and 0.38 $\mu kg/g^{-1}$ dry wt respectively. The highest mercury concentration in an individual fish was registered in d.r. whitefish – 1.4 $\mu kg/g^{-1}$ dry wt.(*Figure 7.2*).

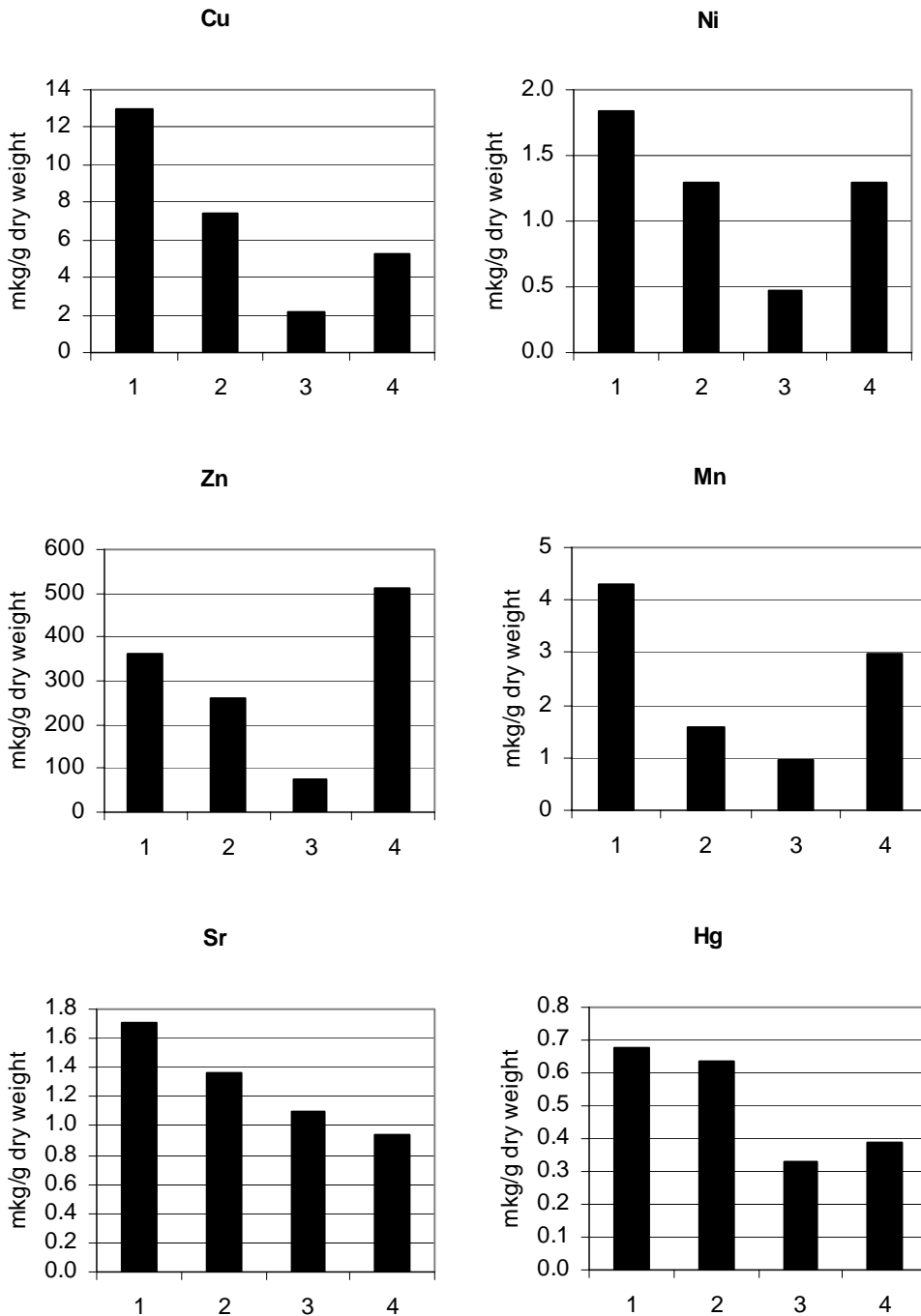

Figure 7.2. Heavy metal concentrations in liver of fish of the Inari Lake in 2004 (1 – sparsely rakered whitefish, 2-densely rakered whitefish, 3-trout, 4-pike).

Kidney. The content of copper in pike was adequately smaller than in whitefish. Nickel and manganese concentrations don't differ much but their content in kidney is smaller. Mean zinc concentrations were considerably high in pike. Strontium more actively accumulated in whitish. The maximum Sr content in a single fish – 2.4 μkg/g^{-1} dry wt was found in whitefish. The same holds for mercury (*Figure 7.3*).

Figure 7.3. Heavy metal concentrations in kidneys of fish of the Inari Lake in 2004 (1 – sparsely rakered whitefish, 2-densely rakered whitefish, 3-trout, 4-pike).

Gill. The analysis of inter-species variability of heavy metal accumulation showed that no adequate difference were revealed in whitefish and pike as regards the accumulation of copper, manganese, strontium and mercury. A considerable excess (two times) nickel contamination was revealed in pike. Pike also had higher mean manganese concentrations (*Figure 7.4*).
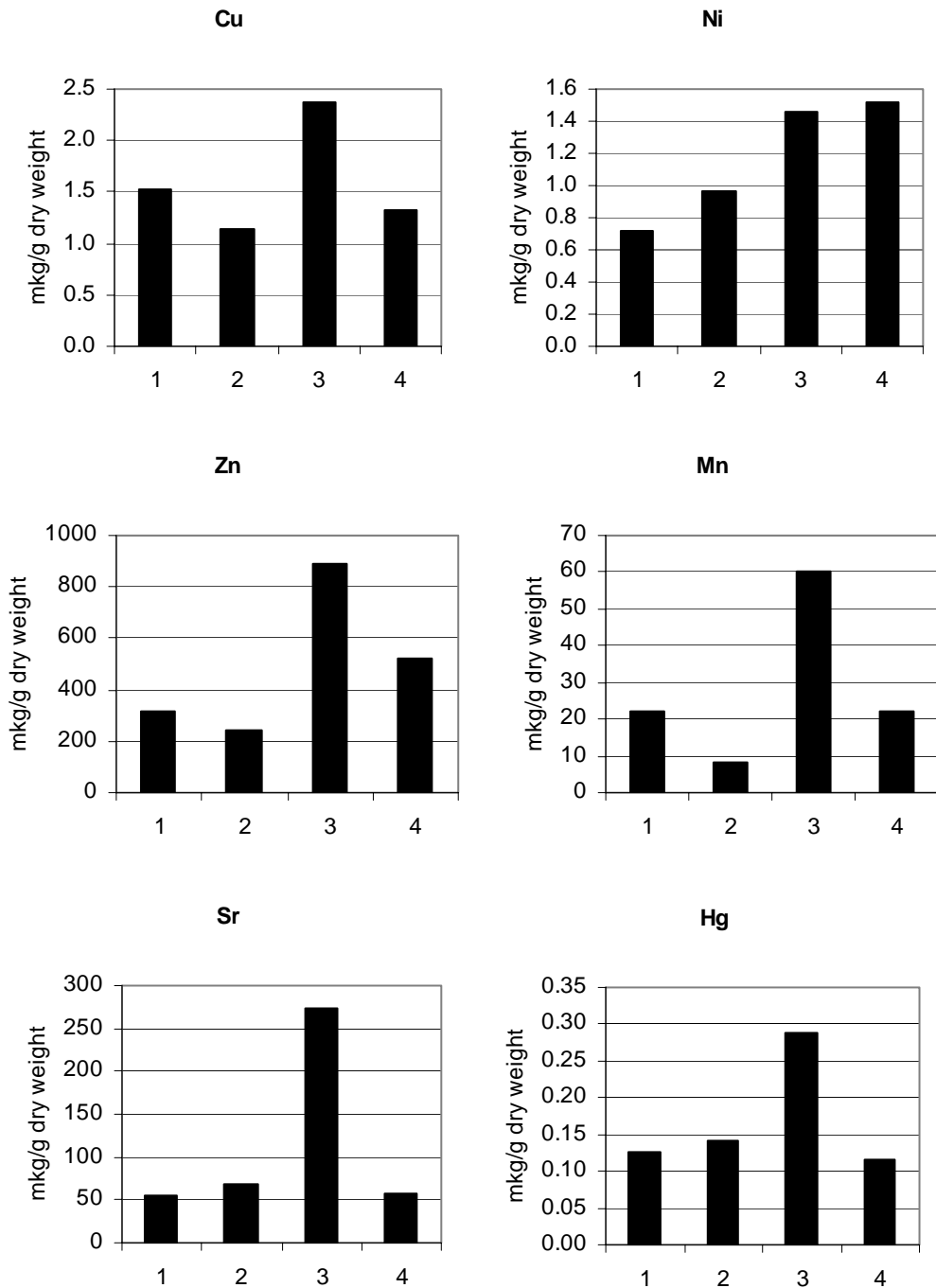

Figure 7.4. Heavy metal concentrations in gills of fish of the Inari Lake in 2004 (1 – sparsely rakered whitefish, 2-densely rakered whitefish, 3-trout, 4-pike).

Skeleton. The concentrations of copper in skeleton of pike were twice as higher than in skeleton of whitefish. The difference in nickel accumulation was even more substantial – three times. Pike had maximum one-time concentration of Ni – 6 μkg/g^{-1} dry wt. The level of zinc accumulation revealed the least inter-species variability. Manganese and mercury accumulated in great amounts in skeleton of pike. The level of strontium accumulation was slightly higher in whitefish (*Figure 7.5*).
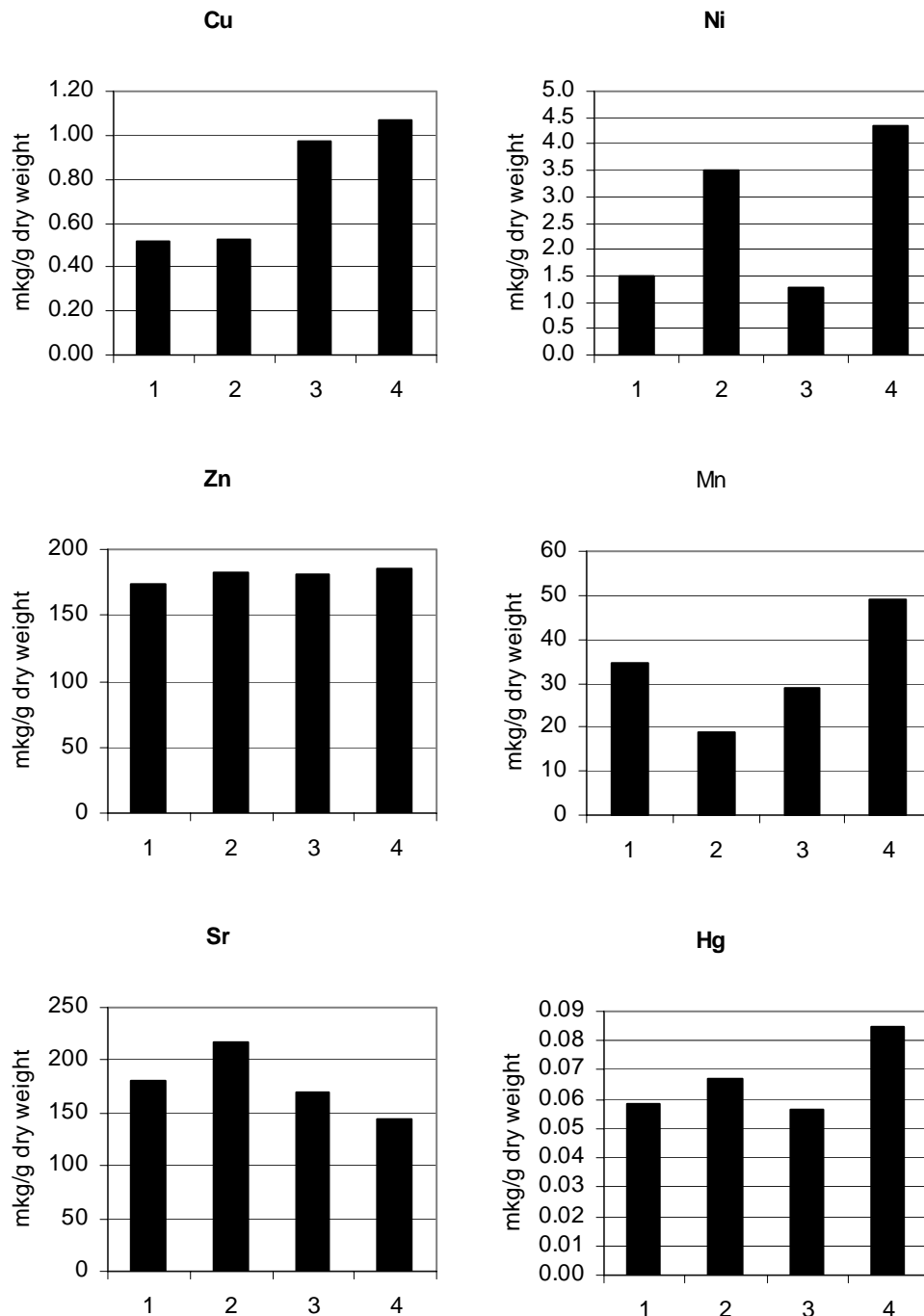

Figure 7.5. Heavy metal concentrations in skeleton of fish of the Inari Lake in 2002 2004 (1 – sparsely rakered whitefish, 2-densely rakered whitefish, 3-trout, 4-pike).

Appendix 8. Detailed presentation of heavy metal contaminations in fish from Stuorajavri

The following fish species from the lake Stuorajavri were examined for heavy metal contaminations: whitefish, pike, trout and perch. Out of all heavy metals the concentrations of zinc were highest in all examined organs.

No dependence was found in distribution of metals in muscle tissues of fish of various trophic levels. The highest concentrations of nickel, manganese and mercury were observed in muscles of pike (Fig.8.1). Copper was accumulated intensively in the muscles of trout and pike. The highest concentrations of zinc were characteristic of the densely rakered whitefish. Both forms of whitefish and pike had practically the same content of strontium (Fig. 8.1). It should be noted that the perch being euryphagous had on the whole less concentrations of the given metals as compared to the other fish species.
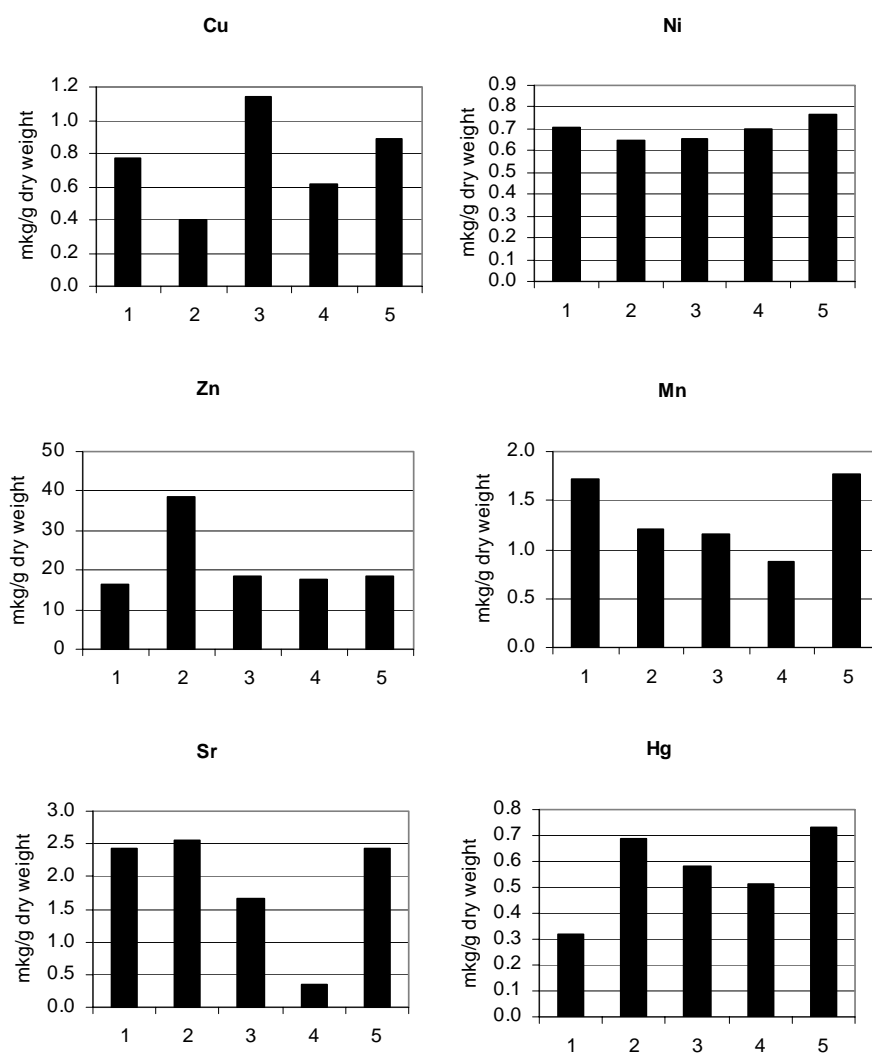

Fig. 8.1. Heavy metal concentrations in muscles of fish from the lake Stuorajavri in 2005. (1- sparesely rakered whitefish, 2- densely rakered whitefish, 3 – trout, 4 – perch, 5 – pike).

The whitefish had the highest heavy metal concentration in liver (Ni, Mn, Hg). Mean concentrations of copper in liver of trout substantially exceeded the same values of other predatory fish species (pike), and constituted over 100 μkg/g dry weight (Fig. 8.2). Pikes had minimum concentrations of manganese, strontium and mercury as compared to other fish species. The densely rakered whitefish had the highest level of mercury in liver (Fig.8.2), which can be explained by its feeding habits. With all that the comparable levels of accumulation of some metals (Zn, Mn, Sr) in both forms of whitefish can be explained by widespread occurrence of these elements in their nutritional ingredients (benthos and plankton). The highest concentrations of nickel were found in liver, in comparison with other organs.
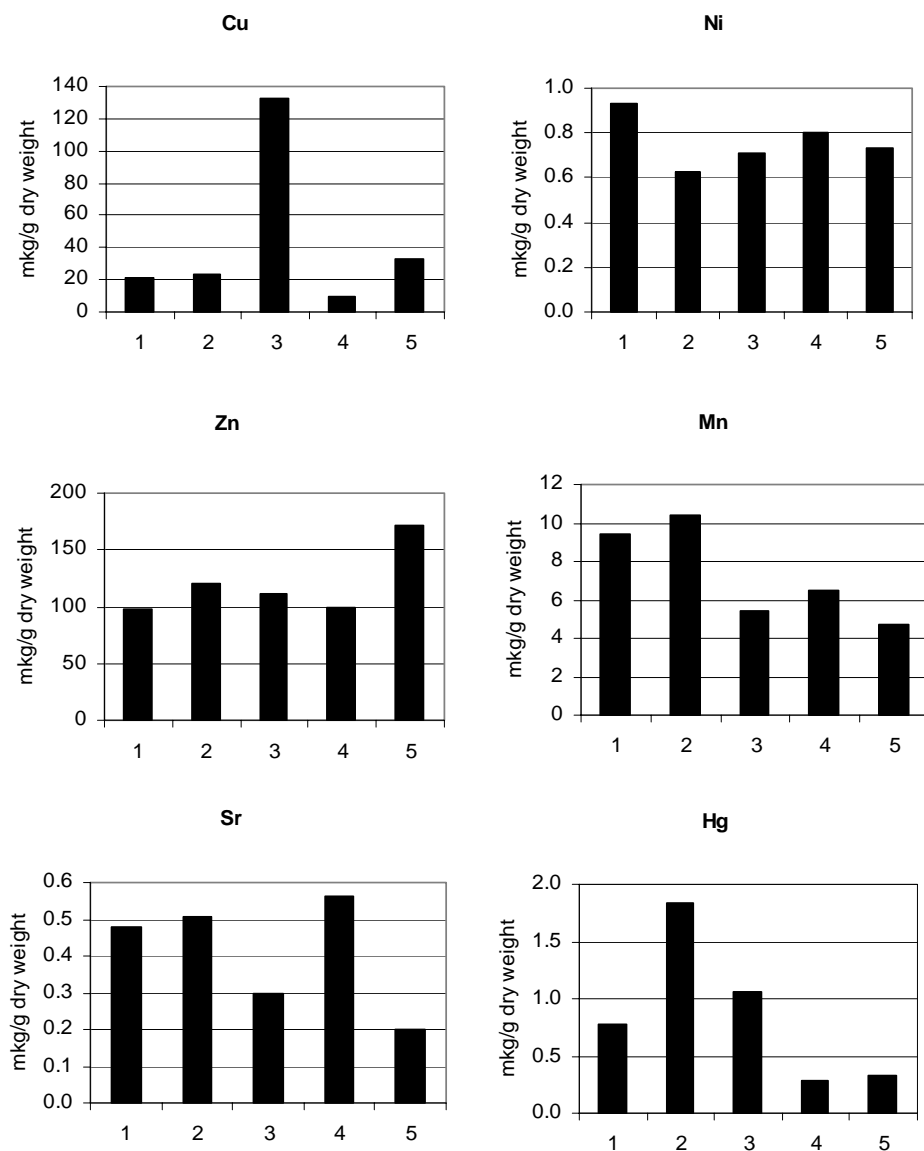

Fig. 8.2. Heavy metal concentrations in liver of the fish from the lake Stuorajavri in 2005 (1-sparesely rakered whitefish, 2- densely rakered whitefish, 3 – trout, 4 – perch, 5 – pike).

Pikes had the highest average concentrations of Zn in kidneys (Fig. 8.3). The same as for liver of the densely rakered whitefish its kidney had maximum concentrations of mercury. Distributions of strontium were the same in the examined fish species.
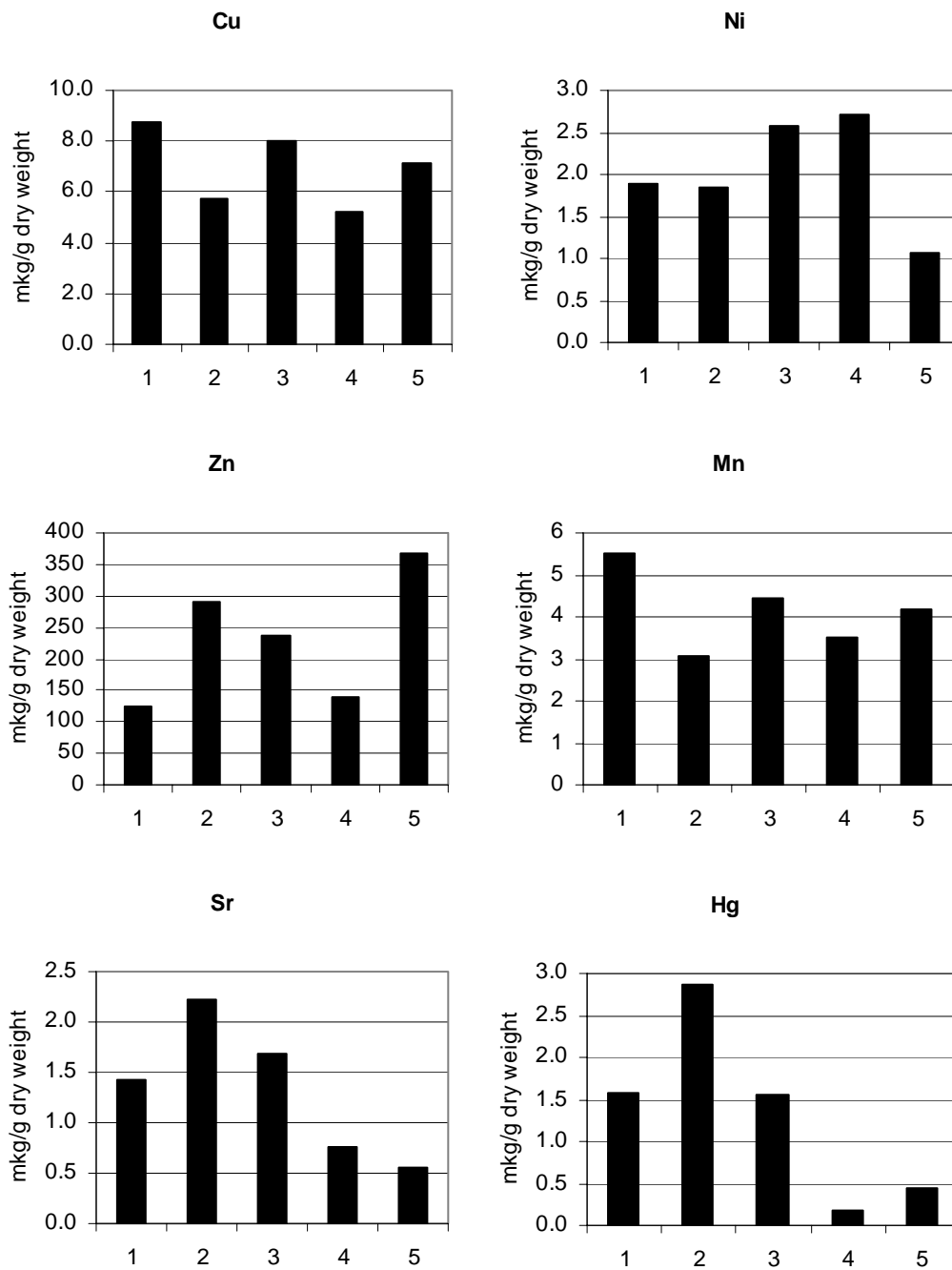

Fig. 8.3. Heavy mental concentrations in kidney of the fish from the lake Stuorajavri in 2005 (1-sparesely rakered whitefish, 2- densely rakered whitefish, 3 – trout, 4 – perch, 5 – pike).

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The main pollutants generated by copper-nickel industry – Ni and Cu and also Mg in gills increased with higher trophic status of fish species (Fig 8.4). The densely rakered whitefish and trout had the highest content of mercury in gills.
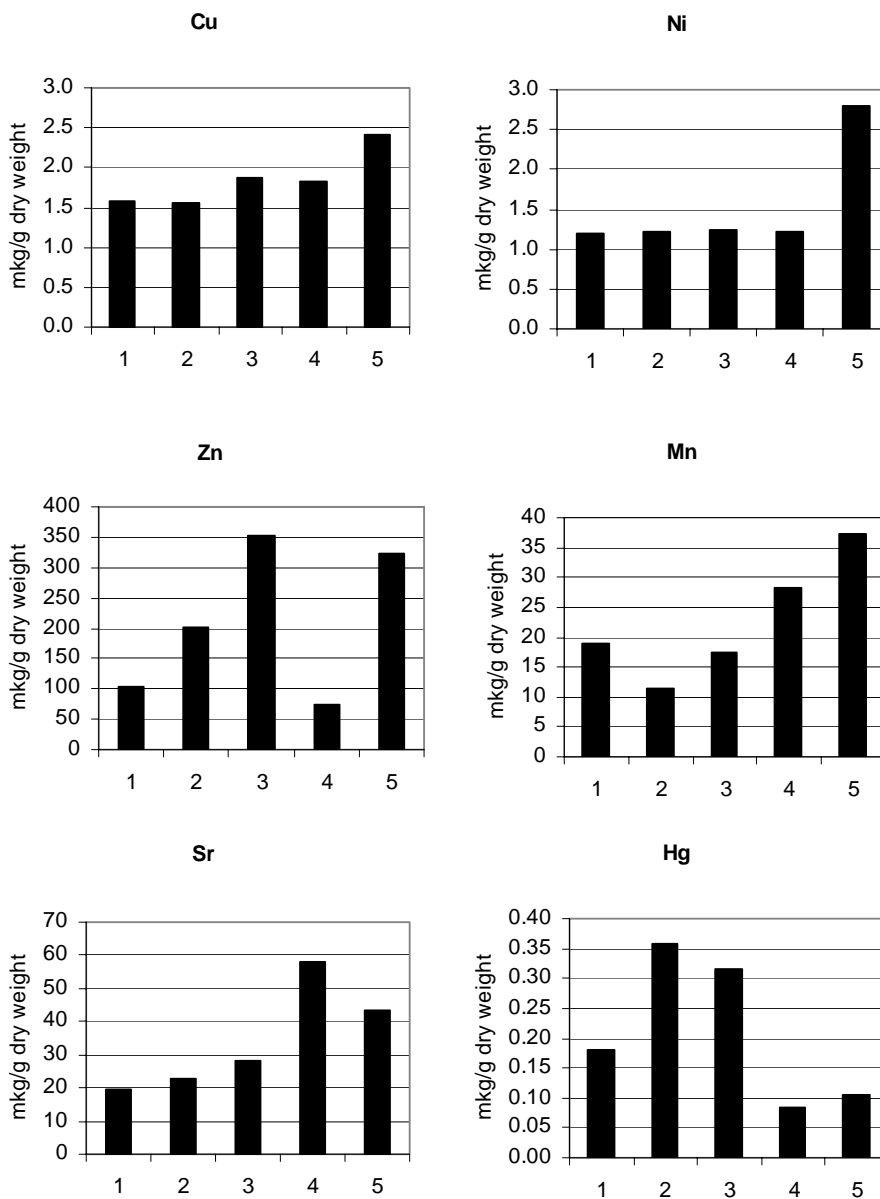

Fig. 8.4. Heavy metal concentrations in gills of the fish from the lake Stuorajavri in 2005 (1-sparesely rakered whitefish, 2- densely rakered whitefish, 3 – trout, 4 – perch, 5 – pike).

The degree of Ni and Cu contaminations in bone tissue of fish increased as follows: whitefish>trout>perch>pike (Fig. 8.5). The other metals didn't submit to such dependence, though perch had higher concentrations of strontium and manganese in skeleton.
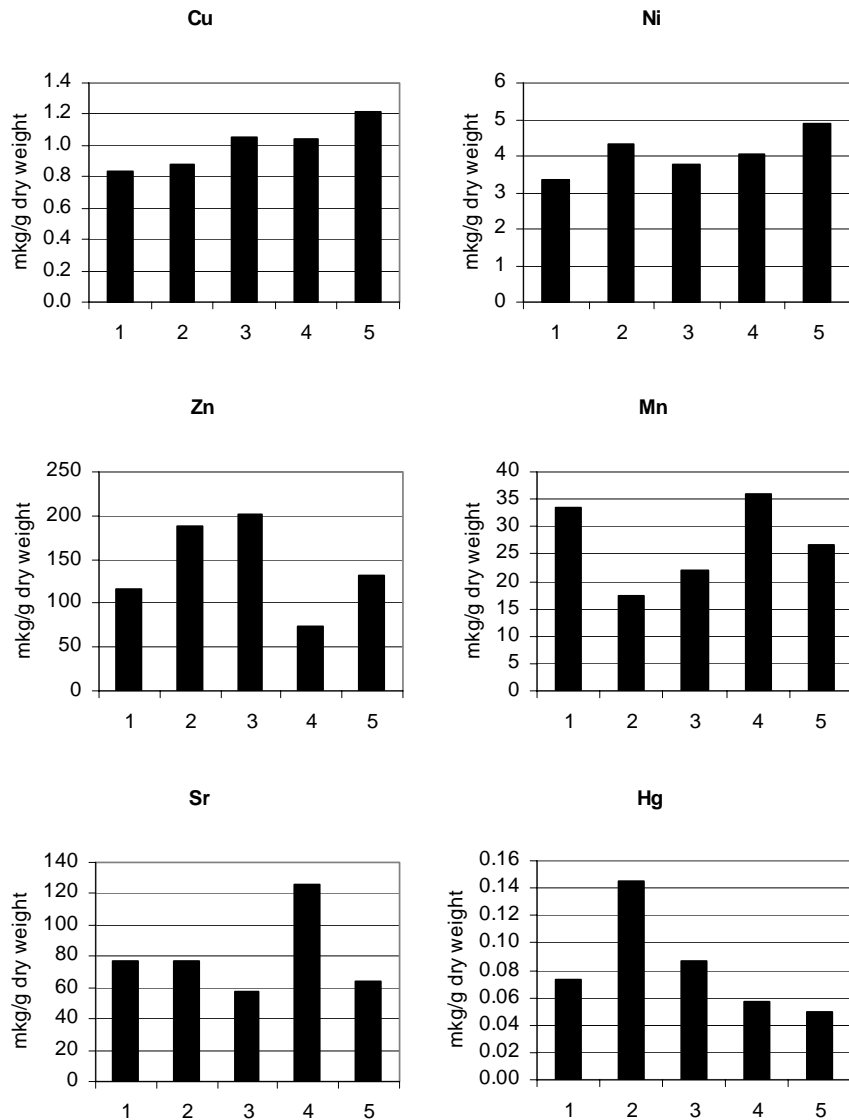
Fig. 8.5. Heavy metal concentrations in skeleton of the fish from the lake Stuorajavri in 2005 (1-sparesely rakered whitefish, 2- densely rakered whitefish, 3 – trout, 4 – perch, 5 – pike)

The highest concentrations of mercury in all organs of d.r.whitefish suggest that plankton feeding type results in higher levels of mercury accumulation in organs of planktiverous fish species. At the same time deposition of excess metals in muscular tissue corresponds with general idea of mercury accumulation in trophic chains (Fig. 8.1). Some general notions on priority metal accumulation in a range of organs were also confirmed. Copper accumulates more actively in liver of fish and nickel – in kidney. Higher concentrations of strontium were observed in skeleton and zinc and manganese – in gills and bone tissue.

Appendix 9. Detailed presentation of results of the pathological studies

The Inari-Paz watercourse.

The studies pursued in the early 1990s first of all revealed changes of structure, color and form of liver, typical of all water bodies of the Inari-Paz watercourse. The color of liver of whitefish was pale and mosaic.

In some isolated cases a segmental structure of liver appeared as the disease progressed. Disorders in kidney (nonuniform structure and connective-tissue expansions) and in gonads (strangulated and twisted gonads and their asymmetric development) ranked next (Kashulin et al. 1999).

The studies of 2002 showed that the frequency of pathologies of gonads, gills and liver decreased notably. At the same time the number of fish with pathologies of kidney and liver increased proliferating in the subsequent studies (2003 – 2005) (Fig. 9.1). Particularly high frequency of changes in these organs was registered in 2003 (up to 88.2 and 84.1 % respectively). The highest frequency of pathologies of gonads and gills of whitefish was registered in 2005, being 19.4 and 28.2% respectively.

The available research data on whitefish of the Skrukkebukta reservoir revealed an increasing number of fish with pathologies of kidney (violation of structure and intensive connective-tissue expansions). Besides, the number of whitefish with disorders in liver increased sharply as compared to the data of 2002 (more than 60%) (Fig. 9.2).

The frequency of changes of gills was highest in 2004 (17.5%), but in the following year 2005 it decreased four times more. On the whole, out of all water bodies of the Inari-Paz watercourse, the whitefish of river undercurrent (Skrukkebukta, Bjornevatn) had highest number of pathologies of liver and kidney (over 70%).
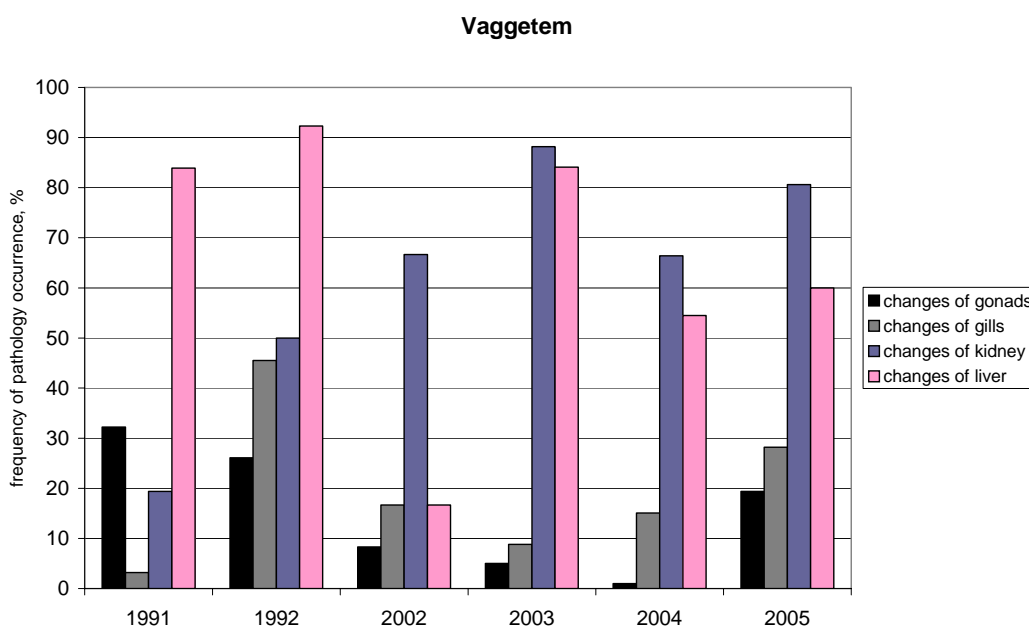

Fig. 9.1. Pathologic changes of inner organs of whitefish in the Vaggetem reservoir in 1991 – 2005.
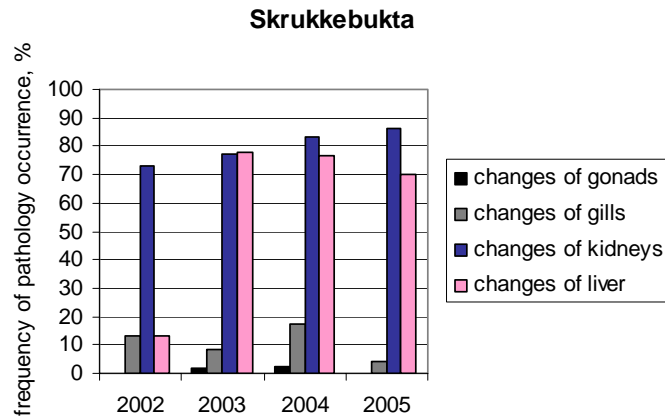
Skrukkebukta

Fig. 9.2. Pathologic changes of inner organs of whitefish in the Skrukkebukta reservoir in 2002 – 2005.

In the water bodies of the Inari-Paz watercourse the frequency of pathologic violations of inner organs of whitefish increased as the water body approaches to the source of air borne industrial pollution ("Pechenganikel" smelter).

It is noteworthy that the most common and serious disorders of inner organs of whitefish were registered in the lake Kuetsjarvi (Fig. 9.3). Against a background of the highest popularity of liver and kidney pathologies, the disorders in reproductive system of fish also outnumbered the other studied water bodies. All fish had decrease of turgor of muscles and depigmentation of skin. Nephrolithiasis was registered only in this region and occurred in more than 9 % of the cases (Fig. 9.3).
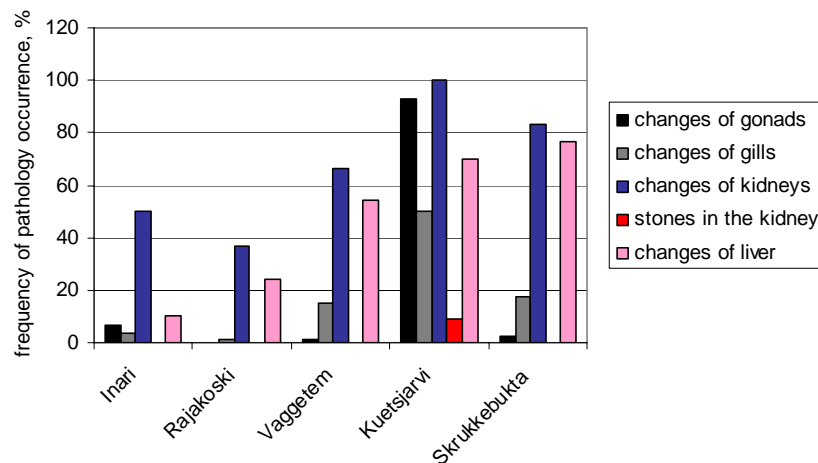

Fig. 9.3. Pathologic changes of inner organs of whitefish in the River Paz in 2004.

The pikes of the Inari-Paz watercourse had all the above named pathologies, found in the fish of the small forest lakes. The intensity and frequency of pathologies was highest in Vaggetem, Skrukkebukta, Bjornevatn and Kuetsjarvi. Pikes of the Rajakoski region had the highest intensity and frequency of greenish color of muscular tissue, mouth and liver (up to 20 and 48%). One sample from the lake Inari had underdeveloped upper jaw. Among the fish from other water bodies of the river system the number of fish with this pathology varied from 29% (Skrukkebukta) to 53.8 % (Bjornevatn). The color of liver of pikes changed from sand-gray to dark green. The highest frequency of this pathology was characteristic for the

fish from Vaggetem, Bjornevatn and Skrukkebukta (50, 53 and 57% respectively) and lake Kuetsjarvi (up to 92 %). The number of fish with greenish or intense green color of mouth and muscular tissue was high in the catches of 2004 in Vaggetem (to 70%) and Skrukkebukta (to 83%).

Lake Stuorajavri

The anatomic dissection data showed that the most frequently found disorders of inner organs of whitefish were connective tissue and granulation in kidney, which occurred in 90% of the instances. The frequency of kidney pathologies was also high and amounted to 50%; they appeared as change of color and degeneration of tissue (mosaicism) (Fig. 9.4). Disorders in the reproductive system were rarest and occurred in the form of anisochronous and asymmetric maturation of gonads (about 6%). Besides the whitefish had irregular raw and warp of rakers in 23% of cases.
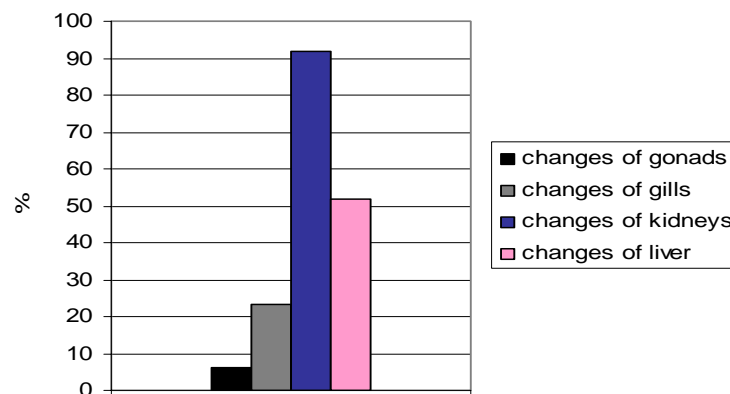

Fig. 9.4. Pathologies of inner organs of whitefish in the lake Stuorajavri in 2005.

As regards pike, which was not abundant in the catches, two fish had unsatisfactory state of liver (28.6%). The liver had greenish color.