

# Effects of iron, aluminium, dissolved humic material and acidity on grayling (*Thymallus thymallus*) in laboratory exposures, and a comparison of sensitivity with brown trout (*Salmo trutta*)

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Iron alone, as well as aluminium, can be acutely lethal in humus-free acidic water. In a simultaneous laboratory exposure to both Fe and Al the toxic effects on grayling were even more pronounced. Water acidity increased and dissolved humic material reduced the toxicity of Fe and Al. As toxic effects, the ionoregulation of yolk-sac fry was disturbed, swimming activity decreased and mortality increased. Based on mortality and swimming activity, brown trout yolk-sac fry tolerated, depending on the Al concentration, nearly half a pH unit more of acidity than those of grayling. The gills of the affected one-summer-old grayling were damaged, leading to decreased oxygen uptake and disturbed ionoregulation. In cold water (3 °C), one-summer-old grayling did not recover completely from the sublethal exposure. Some tributary waters of Isojoki, a river in West-Central Finland, were toxic to grayling yolk-sac fry. These waters had rather high Al and Fe concentrations but were humic and only slightly acidic. It is concluded that increased concentrations of Fe and Al increases the harmfulness of waters in forestry land use or peat production areas even in humic and slightly acidic waters.

## Introduction

Forestry land use often drastically changes the water quality of river systems in the treatment area. The leaching of inorganic and organic suspended solids and concentrations of dissolved organic matter and nutrients may increase as may water flow and temperature (e.g., Ahtiainen 1992). Aluminium, iron and other metals are also leached from the soil and rinsed into river systems (Ahtiainen 1992, Reynolds *et al.* 1992, *see also* Vuori 1995). Metals are at least partially bound by the dissolved organic carbon, i.e. humic material (Kullberg *et al.* 1993). Changes in water pH depend greatly on the soil type (Urho *et al.* 1990, Ahtiainen 1992, Ahti *et al.* 1995, Rees and Ribbens 1995).

The primary toxic effects of metals on fish can mostly be explained by the surface activity of metals as free cations, i.e. metal binding to the respiratory epithelium damages it and its normal functions (McDonald *et al.* 1989, McDonald and Wood 1993). The most important water quality variables affecting metal activity are pH, the calcium concentration and the content of complex forming substances. Humic substances form quite stable complexes with metals decreasing the proportion of ionic metals in the water (McDonald *et al.* 1989, Kullberg *et al.* 1993). On the other hand, humus inhibits the oxidation of toxic ferrous iron to the less toxic ferric form (Suzuki *et al.* 1992). Compared to aluminium, little is known about the toxicity of iron to fish. The effects of iron on fish have been studied primarily in connection with effluent discharges from industry and mining (e.g., Sykora *et al.* 1972, Smith *et al.* 1973, Lehtonen 1976, Smith and Sykora 1976, Vuorinen 1984, Grippo and Dunson 1996a, 1996b).

Aluminium has harmful effects on the different developmental stages of fish in acidic water (e.g., Vuorinen *et al.* 1990, Weatherley *et al.* 1990, Wood *et al.* 1990, Vuorinen *et al.* 1992, 1993, 1994a, 1994b). During long-term exposures in aluminium-containing acidic water, the spawning of fish can be delayed (Beamish *et al.* 1975, Tam and Payson 1986, Rask *et al.* 1990, Vuorinen *et al.* 1990, Vuorinen and Vuorinen 1991, Vuorinen *et al.* 1992). Growth may be slowed if competition for food does not decrease due to lowered numbers of fish species or specimens (Tam and

Payson 1986, Gunn *et al.* 1987, Rask *et al.* 1988, Vuorinen *et al.* 1990, Rask *et al.* 1992, Vuorinen *et al.* 1992). Newly-hatched fry are usually sensitive to acidic and aluminium-containing water, although the yolk-sac fry of some species can survive even days in such aluminium concentrations that would be lethal during a prolonged exposure (Vuorinen *et al.* 1993, 1994b). When gills are fully developed the acute toxicity of aluminium to fish is primarily due to its effects on the gill epithelium disturbing gas exchange and body ionic balance (Neville 1985, Waring and Brown 1995). Changes in the ionic balance have been observed during short and long-term exposures (Weiner *et al.* 1986, Audet *et al.* 1988, Tuunainen *et al.* 1990, Vuorinen *et al.* 1990, McDonald *et al.* 1991, Vuorinen *et al.* 1992). The ionic balance is disturbed and oxygen consumption changed in yolk-sac fry, as well, when exposed to aluminium (Keinänen *et al.* 1998, M. Keinänen, S. Peuranen, M. Nikinmaa and P.J. Vuorinen, unpubl.). There are differences in tolerance between fish species to aluminium (Grande *et al.* 1978, Holtze and Hutchinson 1989, Vuorinen *et al.* 1993, Poléo *et al.* 1997). Nothing was known about the aluminium tolerance of grayling (*Thymallus thymallus*), until recently Poléo *et al.* (1997) reported the median lethal time (410 h) in an aluminium exposure (399 µg Al l<sup>-1</sup>, pH 5.08) for grayling parr.

Iron occurs primarily as a free ferrous form, iron(II), in acidic water (pH < 5.8) when the water oxygen concentration is low (Stumm and Lee 1960). This iron form is deleterious to fish (Decker and Menendez 1974, von Luckowich 1976, Amelung 1982). Newly-hatched rainbow trout (*Oncorhynchus mykiss*) died in an iron(II) concentration of 1.3 mg l<sup>-1</sup> (pH 6–8) (Amelung 1982) and brook trout (*Salvelinus fontinalis*) at pH 5.5 in one day when 3.2 mg l<sup>-1</sup> of iron was added to the water as ferrous sulphate, the 48-hour LC50 value being 0.4 mg l<sup>-1</sup> (Decker and Menendez 1974). The numbers of hatched coho salmon (*O. kisutch*) decreased when the water iron concentration was over 1.0–1.3 mg l<sup>-1</sup> (pH > 7.7). In addition, oxidized iron is deposited on eggs and gills whereupon the diffusion of gases becomes more difficult (Larson and Olsen 1950, Smith *et al.* 1973, Bagge and Ilus 1975, Lehtonen 1976, von Lukowicz 1976, Andersson and Nyberg 1984, Vuorinen 1984, Oulasvirta 1990, Geertz-Hansen

and Rasmussen 1994). The harmful effects of iron will decrease if ferrous iron has time to oxidize into the ferric form before it comes into contact with the fish (Liebmann 1960). In 10 °C sea water, half of the ferrous iron will oxidize into a ferric form within eight days at pH 6, while at pH 5, it may take over two years (Roekens and van Griegen 1983).

When brown trout (*Salmo trutta*) were caged in an acidic river below a liming station, iron and aluminium were observed on their gills (Weatherley *et al.* 1991). Iron, along with aluminium, was suspected to be the cause of death of the caged fish. Andersson and Nyberg (1984) caged brown trout in a river during snow-melt. Fish started to die when melt waters flowed into the river although the water pH was still above 5.5. Water aluminium, iron, and manganese concentrations were 90–160, 550–1 200, and 80–180 µg l<sup>-1</sup>, respectively. Iron was presumed to contribute to the deaths in that test as well. In Finland, iron and aluminium concentrations in river systems can be as much as several milligrams per litre (Hudd *et al.* 1984, Heikkinen 1990, Vuori 1995), though in very high concentrations the greater part of these metals is probably bound to organic matter. The combined effects of aluminium and iron have been studied with lamprey (*Lampetra fluviatilis*): the oxygen consumption of lamprey larvae decreased when they were exposed simultaneously to iron (1.5 mg l<sup>-1</sup>) and aluminium (0.3 mg l<sup>-1</sup>) at pH 5.5 (Saski and Nikinmaa 1990). The toxicity of river water to the newly-hatched larvae of lamprey seemed to be related to the increase in the total iron concentration in the water flowing through sulphide-rich soils (Myllynen *et al.* 1997). Aluminium is known to accelerate the iron and H<sub>2</sub>O<sub>2</sub>-induced peroxidation of erythrocyte membranes *in vitro* (Gutteridge *et al.* 1985).

This investigation aimed at demonstrating the effects of iron and aluminium on grayling and the modifying effects of water acidity and dissolved humic material. A study of the effects on the gills and physiology of one-summer-old grayling was carried out as in our earlier brown trout experiment (Peuranen *et al.* 1994). Because the changes in the water quality of river waters can be short-term, the recovery of one-summer-old grayling from a short-term exposure was studied; the effect of temperature was also tested. The sensitivity of grayling and

brown trout was compared in yolk-sac fry. In addition to different water quality combinations in artificial water, grayling yolk-sac fry were exposed to natural waters from Isojoki, a river in West-Central Finland, and a peat production area and to mixed waters simulating conditions in early spring and rainy periods. Grayling and brown trout were selected as test species because they are common in small rivers and brooks in areas subject to heavy forest treatment and peat production though their stocks have declined, for instance, in the Isojoki system (Laamanen *et al.* 1994).

## Material and methods

In all experiments, aluminium was added as sulphate (Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> × 16H<sub>2</sub>O) and pH was adjusted with sulphuric acid (*see* Vuorinen *et al.* 1993). Iron was added as FeCl<sub>3</sub> × 6H<sub>2</sub>O and FeSO<sub>4</sub> × 7H<sub>2</sub>O, 1:1, and humic acid as a commercial preparation from Fluka (53680) or Aldrich (H1,675-2; in the recovery test).

### Newly-hatched fry

The effects of iron (0, 1, 2, and 5 mg l<sup>-1</sup>), aluminium (0, 100, 200, 400, and 800 µg l<sup>-1</sup>), dissolved humic material (0 and 10 mg l<sup>-1</sup>) and acidic water (pHs 5.0, 5.5, and 6.0) on grayling (*Thymallus thymallus*) yolk-sac fry were tested using an eight-day (192 h) test. The test solutions were prepared in artificial water (described in Peuranen *et al.* 1994 and Keinänen *et al.* 1998) containing no organic matter. In addition, grayling yolk-sac fry were exposed to waters taken from the tributaries of Isojoki, to water flowing into the clarification basin of a peat production area (Koirasuo in Pudasjärvi), and to water leaving that basin. The outflowing “peat water” was also mixed (1:1) with Lohiluoma water (a tributary of Isojoki) or with aluminium-containing (400 µg l<sup>-1</sup>) artificial water, and the water mixtures were acidified to pHs 5.0, 5.5, and 6.0. The aim of these tests was to simulate the situation in spring when peat production waters flow from a clarification basin to a brook, into which acidic aluminium-containing melt waters flow at the same time. Water quality data on the tributary and

peat production waters are given in Table 1.

Yolk-sac fry were kept in glass jars containing about 800 ml of test water. The temperature was 10 °C. At the beginning, there were 10 fry in each jar. The tests were finished when the control fry had utilized their yolk. During the experiments, the swimming activity and mortality of the fry were observed. The swimming activity was registered as the number of swimming (including those resting temporarily on their bellies) or non-swimming fry (lying on their sides). For the analysis of the exchangeable body sodium concentration, fry were sampled as described in Keinänen *et al.* 1998 and extracted with diluted nitric acid, applying the method of Loenn and Oikari (1982). The concentration of Na<sup>+</sup> in the centrifuged extract was measured with a flame photometer (*see* Keinänen *et al.* 1998).

The sensitivity of brown trout (*Salmo trutta* m. *fario* L.) from Luutajoki, a river in southern Finland, stock and grayling to acidic water and aluminium was compared in experiments where newly-hatched yolk-sac fry were exposed to different aluminium concentrations (0, 100, 200, 400, 600, and 800 µg l<sup>-1</sup>) at different pHs (4.00, 4.25, 4.50, 4.75, 5.00, 5.25, and 5.50). The test solutions were prepared with Lake Päijänne water diluted with ion-exchanged water (1:1), so that the final colour was about 10 mg Pt l<sup>-1</sup> and the calcium concentration 0.07–0.08 mmol l<sup>-1</sup>. The fry were kept in polythene bowls containing 1300–1500 ml of test water. At the beginning of the

exposures there were 16 grayling or 10 brown trout in each bowl. Grayling were exposed for seven days (168 h) at 12 °C until the yolk was nearly utilized in the control group. Brown trout were exposed for 32 days (768 h) at 5 °C and still had some yolk left. The test temperatures for the species were selected to be the natural ones. The swimming activity and number of dead fry were observed daily. Effective values for 50% of the yolk-sac fry, EC50 (effective concentration) and EL50 (effective pH level), were calculated as in Vuorinen *et al.* (1993). The values were based on the number of dead and non-swimming fry.

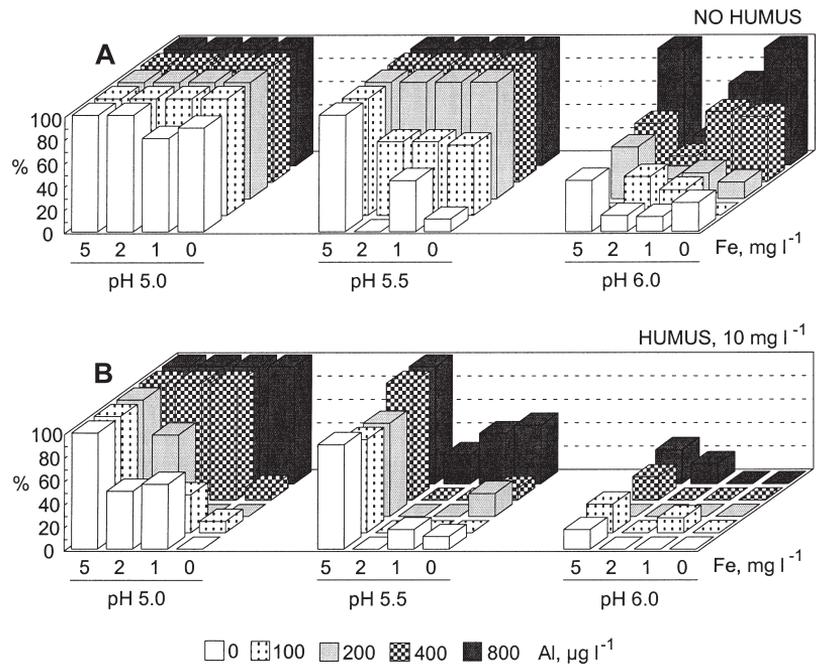
In all yolk-sac fry experiments the test solutions in the exposure vessels were renewed every two to three days. The water renewal inhibited any considerable change in water pH. The tests were carried out similarly to the tests on the effects of aluminium and low pH on the yolk-sac fry of other species (Vuorinen *et al.* 1993), even though there were some differences in water quality.

### One-summer-old fish

In the first experiment, one-summer-old grayling were exposed to iron and aluminium (Fe 2 mg l<sup>-1</sup>, Al 250 µg l<sup>-1</sup>) in artificial water containing dissolved humic material (15 mg l<sup>-1</sup>) and in non-humic water at pHs 5 and 6. The duration of the exposure was three days and the temperature 10 °C. In the second experiment, grayling were

**Table 1.** Water quality data of test waters from the tributaries of Isojoki, two samples of waters entering the clarification basin of a peat production area (Koirasuo in Pudasjärvi) and two samples of waters leaving that basin in 1993.

	pH	Conductivity mS m <sup>-1</sup>	Colour mg Pt l <sup>-1</sup>	Ca <sup>2+</sup> mmol l <sup>-1</sup>	Fe, µg l <sup>-1</sup>	Al <sub>tot</sub> , µg l <sup>-1</sup>
Lohiluoma, 28 May	7.07	1.8	80	0.028	509	149
Hukanluoma, 28 May	6.76	2.0	80	0.029	437	115
Pajuluoma, 28 May	6.94	3.3	160	0.067	811	496
Kärjenluoma, 28 May	6.61	4.0	280	0.083	1 210	385
Hanhioja, 11 June	6.32	3.4	280	0.098	1 710	439
Kärjenluoma, 11 June	6.24	3.7	340	0.104	2 220	440
Ohriluoma, 11 June	5.78	2.3	190	0.044	1 040	707
Peat, entering I, 2 June	7.00	7.3	160	0.129	3 780	98
Peat, entering II, 2 June	6.78	7.5	160	0.150	3 950	126
Peat, leaving I, 2 June	7.01	8.9	130	0.161	3 090	80
Peat, leaving II, 2 June	6.96	9.1	140	0.160	3 820	103



**Fig. 1.** The percentage of affected (dead or non-swimming) newly-hatched grayling fry exposed for eight days at three pHs (5.0, 5.5, and 6.0) to different concentrations of iron (0, 1, 2, and 5 mg l<sup>-1</sup>) and aluminium (0, 100, 200, 400, and 800 µg l<sup>-1</sup>) in (A) water with no humus and (B) with 10 mg l<sup>-1</sup> of dissolved humic material.

exposed to lower iron and aluminium concentrations (Fe 1 mg l<sup>-1</sup>, Al 100 µg l<sup>-1</sup>, humus 15 mg l<sup>-1</sup>) at pH 5.5 at two different temperatures (3 and 13 °C) for six days, after which they were transferred to metal-free water for a seven-day recovery. The water volume in the test tubs was 50–60 l. At the beginning of the exposures, there were 12–13 fish in each tank. At the end of the exposures and at the end of the recovery period in the second test, the oxygen consumption of the fish was measured (as described in Peuranen *et al.* 1994) and blood samples were taken from dorsal veins (see Vuorinen *et al.* 1992, Peuranen *et al.* 1994) for the determination of the plasma chloride concentration (see Vuorinen *et al.* 1990). Gill samples were processed using the paraffin technique as described in Peuranen *et al.* (1994) and the gill slices were studied using a light microscope.

The test solutions in the tubs were renewed once or twice a day. The water was also aerated during the experiments. The fish were not fed, and feeding was stopped two days before the beginning of the exposures.

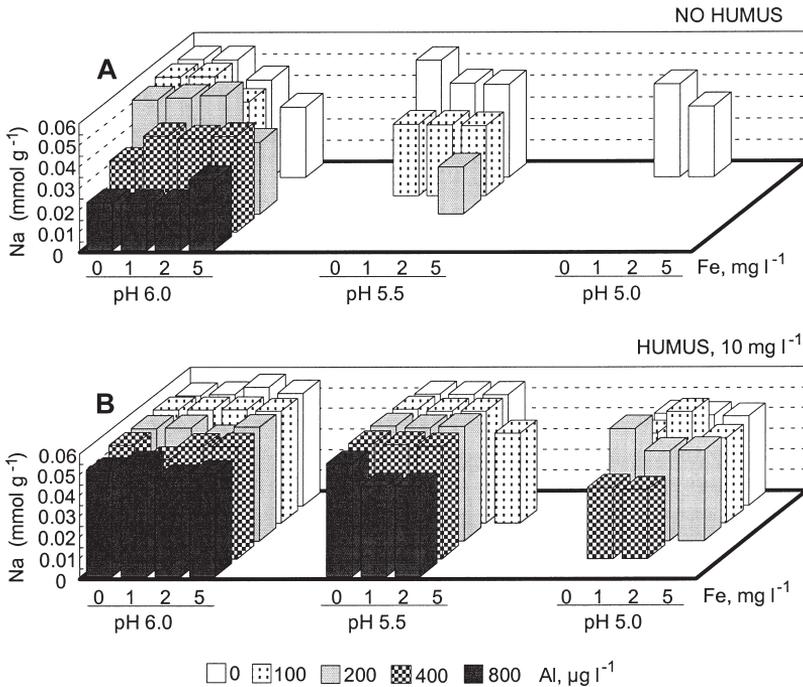
The effects of the treatments were tested with one-way ANOVA and the differences between the means with Tukey's test at the 95% confidence level (SAS 1988).

## Results

### Newly-hatched fry

Dissolved humic material reduced the toxicity of iron and aluminium to the yolk-sac fry of grayling (Figs. 1 and 2). However, iron and aluminium decreased the swimming activity and exchangeable body sodium concentration of grayling yolk-sac fry up to pH 6 in water containing humus as well (Figs. 1 and 2). The ion balance (the exchangeable body Na<sup>+</sup> concentration) of the grayling yolk-sac fry was disturbed at pH 5.0 (Fig. 2) before any decrease in swimming activity was detected (Fig. 1). Dissolved humic material was also beneficial in acidic water which contained no iron or aluminium.

The humic water of Ohriluoma (a tributary of Isojoki) which contained high aluminium and rather high iron concentration (Table 1), was acutely lethal to grayling yolk-sac fry and the ionoregulation of the surviving fry was disturbed (Fig. 3). The swimming activity of the fry decreased in Pajuluoma water (Fig. 3), although the water pH was nearly neutral (Table 1). The exchangeable body Na<sup>+</sup> concentration of the fry exposed to Hanhioja water was also lower than nor-



**Fig. 2.** The exchangeable body sodium concentration of the grayling yolk-sac fry alive after exposure for eight days at three pHs (5.0, 5.5, and 6.0) to different concentrations of iron (0, 1, 2, and 5 mg l<sup>-1</sup>) and aluminium (0, 100, 200, 400, and 800 µg l<sup>-1</sup>) in (A) water with no humus and (B) with 10 mg l<sup>-1</sup> of dissolved humic material.

mal (Fig. 3). These effects were not detected in the water of Kärjenluoma which contained the greatest amount of dissolved humic material of these waters (Table 1 and Fig. 3). When the water leaving the clarification basin of peat production waters was added (1:1) to the non-toxic water of Lohiluoma and the mixture was acidified, the swimming activity of grayling decreased and some deaths occurred. The water leaving the clarification basin of peat production waters was even more harmful when aluminium-containing ion-poor artificial water was added (1:1) to it and the mixture was acidified to simulate melt waters (Fig. 3).

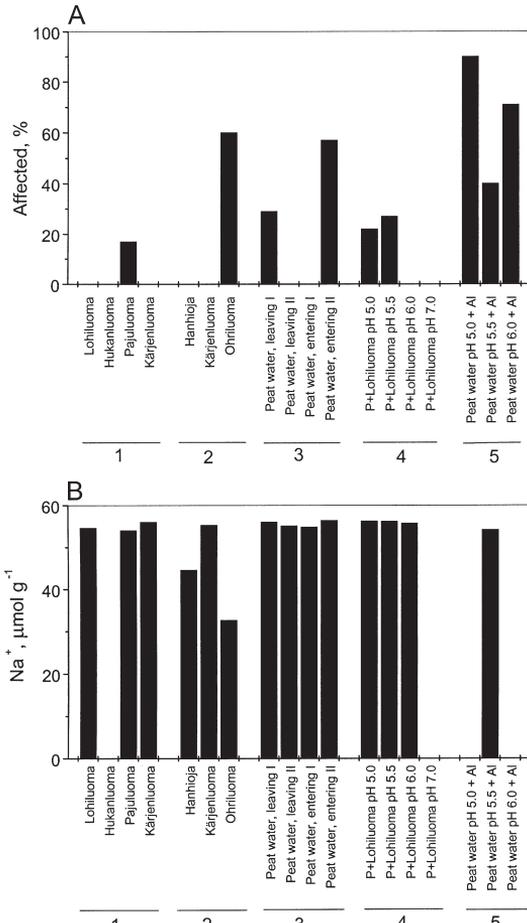
Based on mortality and swimming activity, the newly-hatched fry of grayling were more sensitive to acidity and aluminium than brown trout yolk-sac fry (Figs. 4 and 5). Brown trout seemed to tolerate nearly half a unit lower of pH than grayling. However, near pH 5 an aluminium concentration of 400 µg l<sup>-1</sup> or more was very deleterious to brown trout as well. On the other hand, brown trout yolk-sac fry might tolerate these test waters even at pH 4.5 if the water contained only a small amount of aluminium (Fig. 5).

### One-summer-old fish

In three days, 23% of the one-summer-old grayling exposed to iron (2 mg l<sup>-1</sup>) and 8% of grayling exposed to aluminium (250 µg l<sup>-1</sup>) died at pH 5 and none at pH 6 (Table 2). When grayling were exposed simultaneously to iron (2 mg l<sup>-1</sup>) and aluminium (250 µg l<sup>-1</sup>), 69% of the fish died at pH 5 and 8% at pH 6. Fifty per cent of the grayling died in six days exposed simultaneously to 1 mg l<sup>-1</sup> of iron and 100 µg l<sup>-1</sup> of aluminium at pH 5.5.

The gills of the grayling exposed to aluminium and iron had deteriorated, i.e. the gill lamellae were typically adhered and the epithelial cells damaged (Fig. 6). The plasma chloride concentration (Fig. 7) and the oxygen consumption (Fig. 8) of fish were lower compared to the control ( $p < 0.05$ ).

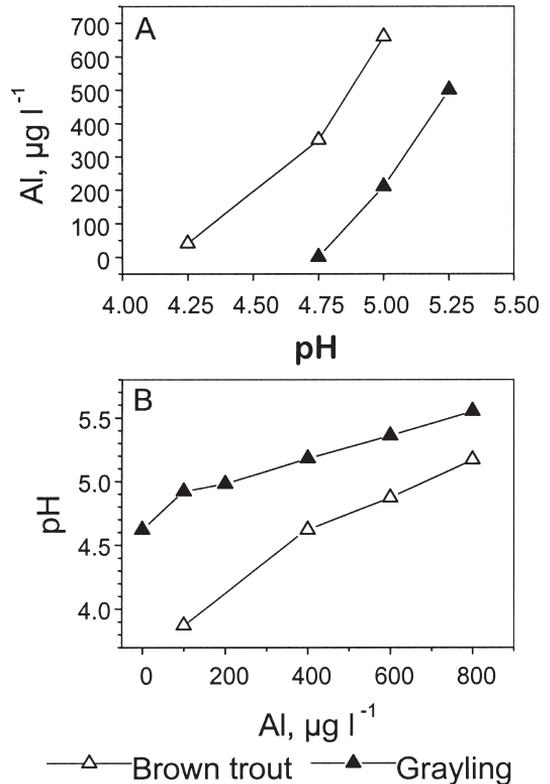
Adding dissolved humic material (15 mg l<sup>-1</sup>) to the water reduced the toxic effects of aluminium and iron and no grayling died. Gill damage was reduced (Fig. 6) and ionoregulation was not disturbed (Fig. 7). The decrease in metal toxicity due to dissolved humic material was also seen as improved capacity for oxygen uptake (Fig. 8). How-



**Fig. 3.** (A) The percentage of affected (dead or non-swimming) newly-hatched grayling fry and (B) the exchangeable body sodium concentration of the fry after an eight-day laboratory exposure in different test waters (water quality data are given in Table 1): (1) the waters from the tributaries of Isojoki taken on 28 May and (2) 11 June; (3) two water lots entering the clarification basin of peat production waters and two water lots leaving that basin; (4) leaving "peat water" mixed 1:1 with acidified Lohiluoma water and (5) leaving "peat water" mixed with artificial acidified water containing aluminium (the final concentration of added aluminium was 200  $\mu\text{g l}^{-1}$ ).

ever, oxygen consumption in the presence of humus was still lower than in the control.

After seven days in 13 °C control water, the gills of grayling were almost completely recov-

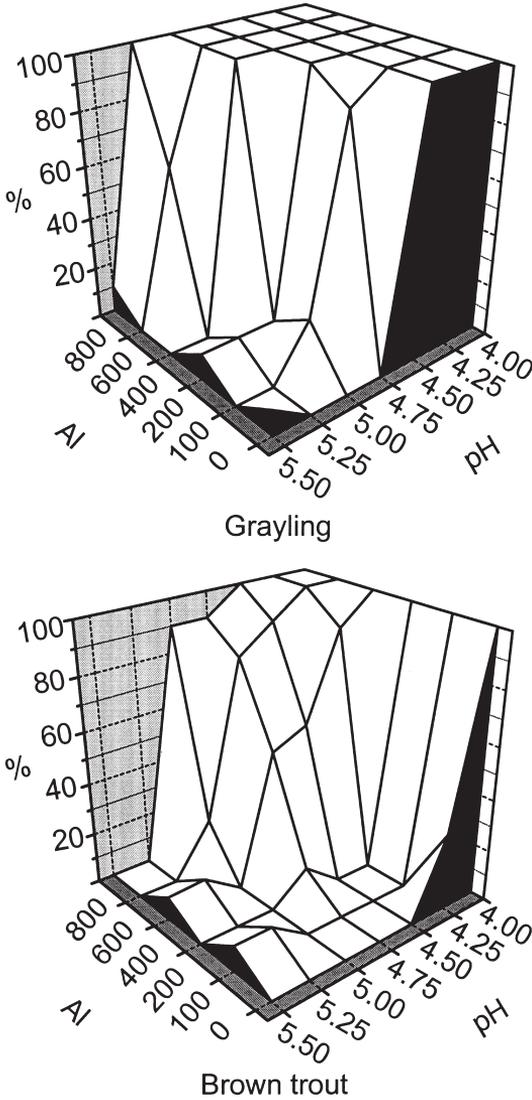


**Fig. 4.** (A) The EC50-values of aluminium at different pHs and (B) the EL50-values of pH in different concentrations of aluminium for grayling after a seven-day exposure at 12 °C and for brown trout from the Luutajoki stock after a 32-day exposure at 5 °C. Effective values for 50% of the yolk-sac fry are based on the number of dead or non-swimming.

ered from the six day simultaneous exposure to 100  $\mu\text{g l}^{-1}$  of aluminium and 1 mg  $\text{l}^{-1}$  of iron, even though the epithelial cells were still swollen. At 3 °C, the gills had not recovered and the lamellae remained attached to each other. Ionoregulation in the grayling had also recovered within one week at 13 °C, but not at 3 °C (Fig. 9).

## Discussion

The gills of one-summer-old grayling were damaged, leading to decreased oxygen uptake and disturbed ionoregulation, in iron and aluminium



**Fig. 5.** The percentage of affected (dead or non-swimming) newly-hatched fry in different pHs and aluminium concentrations ( $\mu\text{g l}^{-1}$ ); grayling after a seven-day exposure at 12 °C and brown trout from the Luutajoki stock after a 32-day exposure at 5 °C.

concentrations found in areas influenced by forestry treatments (Ahtiainen 1992). As well, the ionoregulation was disturbed and swimming activity decreased in grayling yolk-sac fry. In natural conditions, the decrease of swimming activity alone increases the susceptibility of fry to predation. The exchangeable body sodium concentrations of grayling yolk-sac fry changed at pH 5 even in humic water before any alteration in swim-

ming activity could be seen. Ionic disturbance is a well-known response in fish exposed to acidic and aluminium containing water (e.g., Muniz and Leivestad 1980, Neville 1985, Vuorinen *et al.* 1990, Keinänen *et al.* 1998). In a thirty-day exposure at pH 6.5 in soft water (Reader *et al.* 1989) both aluminium, 162  $\mu\text{g l}^{-1}$ , and iron, 39  $\mu\text{g l}^{-1}$ , reduced the sodium, potassium and calcium whole body content of brown trout yolk-sac fry. In that study water ion concentrations were very similar to the concentrations of the artificial low ionic strength water used in the present study.

The iron concentration of 2  $\text{mg l}^{-1}$  in humus-free acidic (pH 5) water was acutely nearly as lethal to one-summer-old grayling as it was to brown trout (Peuranen *et al.* 1994). Toxic effects were more pronounced in simultaneous exposure to aluminium and iron even as lower concentrations. The addition of dissolved humic material in the water clearly reduced the toxicity of aluminium and iron. The humus preparations used in the present experiments may have a different binding affinity to metals compared to the humic sub-

**Table 2.** The mortalities of one-summer-old grayling after being exposed to different concentrations of aluminium and iron in humic or humus-free water. No fish died in any of the control groups.

Exposure time	pH	Temp. °C	Al $\mu\text{g l}^{-1}$	Fe $\text{mg l}^{-1}$	Humus $\text{mg l}^{-1}$	Mortality %
3 d	5.0	10	0	0	0	0
			0	0	15	0
			250	0	0	8
			250	0	15	0
			0	2	0	23
			0	2	15	0
	6.0	10	250	2	0	69
			250	2	15	0
			0	0	0	0
			0	0	15	0
			250	0	0	0
			250	0	15	0
6 d	5.5	13	0	0	0	0
			100	1	0	50
			100	1	15	0
	5.5	3	0	0	0	0
			100	1	0	0
			100	1	15	0

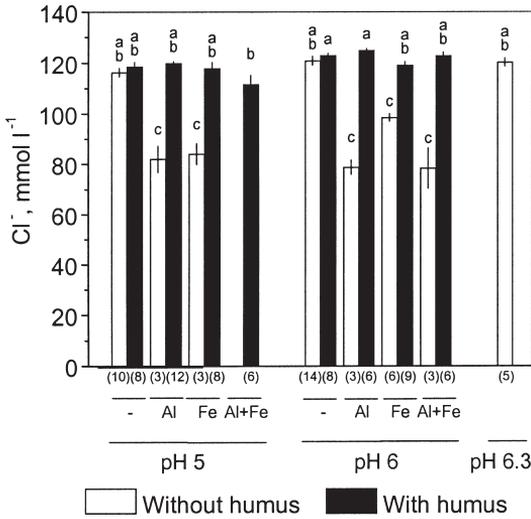


**Fig. 6.** Gill lamellae of one-summer-old grayling exposed for three days at 10 °C to iron and aluminium (Fe 2 mg l<sup>-1</sup>, Al 250 µg l<sup>-1</sup>) at pH 6 (A) without humus and (B) with 15 mg l<sup>-1</sup> of dissolved humic material. (C) Gills of the control group, pH 6.3. Adhered gill lamellae are indicated with an arrow.

stances in natural waters (Kukkonen 1991). The protecting effect of humus was also seen in the exposures of grayling yolk-sac fry to natural waters, one of which (i.e., with high humic material content) was not toxic in spite of a high aluminium and iron concentration. Similarly, of acidic brook waters containing moderate amounts of aluminium and iron, those with a higher humus content were less toxic to rainbow trout than were low-humic waters (Hulsman *et al.* 1983). Humus has previously been shown to reduce the acute toxicity of aluminium (Baker and Schofield 1980), while the growth of juvenile rainbow trout in an exposure to aluminium was better in water with dissolved humic material than in humus-free water (Gundersen *et al.* 1994). According to Roy and Campbell (1997), natural organic matter may play an independent protective role in acidic aluminium-containing water in addition to decreasing aluminium toxicity by complexation. In the present study, dissolved humic material alone was

beneficial to the yolk-sac fry of grayling in ion-poor acidic water which did not contain any aluminium or iron.

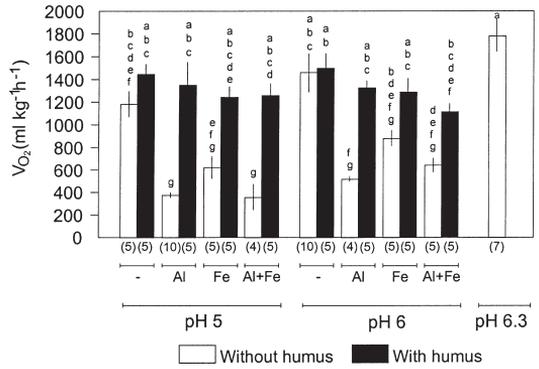
Humic material did not entirely ameliorate the toxicity of aluminium and iron. Even at pH 6 with dissolved humic material and a colour corresponding to the colour of natural waters, the metals had toxic effects on grayling yolk-sac fry as well as on the oxygen consumption of one-summer-old grayling. The sodium content of yolk-sac fry was lower and swimming activity also decreased in humic water. Some of the fry even died when exposed to a tributary water from the River Isojoki containing high concentrations of aluminium and iron but also dissolved humic material. These natural waters were not very acidic, with the lowest pH being just below six. The most toxic of the tested river waters had the highest aluminium concentrations. The aluminium tolerance of fish is known to depend on the ionic strength of water, in particular the calcium concentration, in addi-



**Fig. 7.** Plasma chloride concentration (mean ± SE) of one-summer-old grayling exposed for three days at 10 °C to iron or/and aluminium (Fe 2 mg l<sup>-1</sup>, Al 250 µg l<sup>-1</sup>) at pHs 5 and 6 without humus or with dissolved humic material (15 mg l<sup>-1</sup>). Number of fish measured in brackets. A significant difference ( $p < 0.05$ ) between the groups is indicated by dissimilar letters above the columns. pH 6.3 = control.

tion to pH and dissolved organic matter content (McDonald *et al.* 1989, Playle *et al.* 1989, Lydersen *et al.* 1990, Gundersen *et al.* 1994, Vuorinen *et al.* 1994b, 1995, Keinänen *et al.* 1998). According to Waring and Brown (1995), water aluminium and calcium concentrations affect the physiology of fish as much as the pH.

Water acidity was one of the most essential environmental factors which affected the density of the brown trout population in the tributaries of Isojoki (Juttila *et al.* 1998). However, in addition to physical properties no other water quality parameters but pH and conductivity were available for that study. In a study where a number of water quality characteristics were measured, the catch per unit effort for brown trout was highest in acidified lakes with the highest calcium concentration and acid neutralizing capacity in inflowing secondary streams (Hesthagen and Jonsson 1998). Reader *et al.* (1989) also suggest that aluminium cannot be regarded as the only metal affecting the decline of fish populations in acidic waters. Natural waters may also contain other deleterious metals, such as manganese, which disturbs the ion uptake of brown trout yolk-sac fry even at pH 6.5



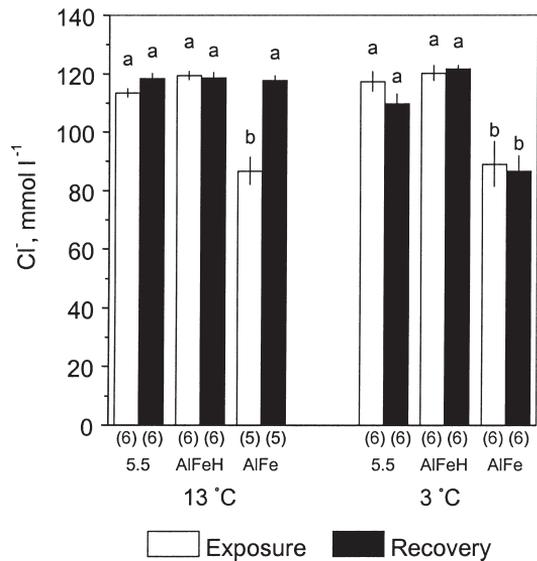
**Fig. 8.** Oxygen consumption (mean ± SE) of one-summer-old grayling at pHs 5 and 6 exposed for three days to iron (2 mg l<sup>-1</sup>) or/and aluminium (250 µg l<sup>-1</sup>) without humus or with dissolved humic material (15 mg l<sup>-1</sup>). Number of fish measured in brackets. A significant difference ( $p < 0.05$ ) between the groups is indicated by dissimilar letters above the columns. pH 6.3 = control.

(Reader *et al.* 1989). According to Kännö (1993), there are a higher number of grayling in waters with high pH, alkalinity and conductivity and low iron concentration. Due to the interactivity of the different water quality parameters, evaluation of the significance of their effects on fish in the natural environment may be difficult.

One-summer-old grayling seemed to be somewhat more tolerant than brown trout in the acute test to iron (Peuranen *et al.* 1994) in terms of mortality and ionoregulation, because the ionic balance in brown trout was disturbed in iron-containing water (2 mg l<sup>-1</sup>) even in the presence of dissolved humic material. There were more alterations in the gills of brown trout than grayling when the fish were exposed to iron in water with dissolved humic material, thus humus seemed to protect one-summer-old brown trout less than grayling. In the study by Poléo *et al.* (1997), grayling parr were somewhat more sensitive than brown trout to aluminium in acidic water based on median lethal times. Accordingly, in the present study, the yolk-sac fry of grayling were more sensitive to aluminium than those of brown trout. The newly-hatched fry of a species with a long yolk-sac phase, such as brown trout, are not very sensitive to aluminium in a short-term exposure (Tuunainen *et al.* 1991). This may be explained by the great number of mucous cells in the skin of newly-hatched fry because the mucus forms com-

plexes with aluminium and thus protects the fish against aluminium (Hughes 1985). In newly-hatched fry without well-developed gills the gas exchange (Rombough 1988) and probably the ion exchange as well (Alderdice 1988, Li *et al.* 1995) occur mainly through the skin. In brown trout fry, the number of skin mucous cells is highest immediately after hatching, approximately twice as high as in older fry (Blackstock and Pickering 1982). The yolk-sac phase of the brown trout lasted several weeks at 5 °C while that of grayling at 12 °C took only about one week. Although the test with brown trout yolk-sac fry continued considerably longer (32 d) than with grayling fry (7 d), the yolk of the grayling was completely absorbed by the end of the test period whereas brown trout fry still had yolk left. However, newly-hatched fry are proposed to be more sensitive than older fry if the exposure continues for the entire yolk-sac phase (Tuunainen *et al.* 1987). When the acute toxicity of many inorganic substances (e.g. metals) to the yolk-sac fry of grayling, rainbow trout and coho salmon were compared, grayling was the most sensitive species, but when older fry were compared there were hardly any differences in sensitivity between the species (Buhl and Hamilton 1991). Brown trout parr were also more tolerant to aluminium than yolk-sac fry (Weatherley *et al.* 1990).

As discharges from the forestry treatment areas can sometimes be short-term peaks, it is important for the survival of the fish that their gills recover from possible damage caused by metals. The gill epithelium is able to recover in a few days, and after the recovery, the metal tolerance of the gills improves (McDonald and Wood 1993). In the test with one-summer-old grayling, recovery took place at 13 °C but no longer at 3 °C. Though there were no mortalities at 3 °C, the low temperature in itself did not protect the fish against the toxicity of the metals. The low mortality in the cold water was most probably due to a slowed metabolism and reduced oxygen demand alone. However, the damage to the gill epithelium under cold conditions possibly prevented the recovery of ionoregulation. The inability of the gill epithelium to recover from the metal exposure in cold water can be fatal to fish in the spring, for example, when waters are still cold. The harmfulness of the melt waters to brown trout has been ob-



**Fig. 9.** Plasma chloride concentration (mean ± SE) of one-summer-old grayling exposed to iron and aluminium with or without dissolved humic material for six days at pH 5.5 and after a one-week recovery. Experiments were performed at 3 °C and at 13 °C. AIFe = iron (1 mg l<sup>-1</sup>) and aluminium (100 µg l<sup>-1</sup>), AIFeH = iron (1 mg l<sup>-1</sup>) and aluminium (100 µg l<sup>-1</sup>) plus dissolved humic material (15 mg l<sup>-1</sup>). Number of fish measured in brackets. A significant difference ( $p < 0.05$ ) between the groups is indicated by dissimilar letters above the columns.

served in caging experiments in a river (Andersson and Nyberg 1984). Furthermore, the oxidation of the toxic ferrous iron to a ferric form is slowed down at low temperatures (Decker and Menendez 1974, Amelung 1982, Roekens and van Griegen 1983).

Melt waters or autumn rains can increase the harmfulness of changes in water quality caused by forestry land use. They can increase the acidity and/or the metal concentrations of the waters, and changes in water pH change the form in which iron and aluminium occur. Dissolved humic material forms complexes with metal ions (Petersen *et al.* 1987, Kukkonen 1991) thereby either increasing or decreasing the bioavailability of metal ions (Kullberg *et al.* 1993). In natural conditions, fish are acclimatized to low metal concentrations and will thus better tolerate the short-term increases in metal concentrations (Mount *et al.* 1990), but this is not the case with newly-hatched fry.

## Conclusions

Aluminium and iron, in concentrations found in the natural environment, may be toxic both to brown trout and grayling, and the toxicity of these metals is augmented with increasing acidity. Even in slightly acidic water, the increase in the concentrations of these metals will make the water more harmful to fish. Dissolved humic substances reduce the toxicity of iron and/or aluminium but do not entirely prevent it. Waters in forest drainage and peat production areas can have toxic effects on fish particularly during spring-melt and autumn rains, because in cold water fish cannot recover quickly from the gill damage caused by the metals. The experiments with yolk-sac fry showed that some natural waters in the areas influenced by forestry treatments and peat production are harmful to the physiology of the fish and some waters can even be acutely lethal.

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## References

- Ahti E., Alasaarela E. & Ylitolonen A. 1995. Kunnostusojituksen vaikutus ojitusalueen hydrologiaan ja valumavesien ainepitoisuuksiin. In: Saukkonen S. & Kenttämies K. (eds), *Metsätalouden vesistövaikutukset ja niiden torjunta. METVE-projektin loppuraportti. Suomen ympäristö 2*: 157–168.
- Ahtiainen M. 1992. The effects of forest clear-cutting and scarification on the water quality of small brooks. *Hydrobiologia* 243: 465–473.
- Alderdice D.F. 1988. Osmotic and ionic regulation in teleost eggs and larvae. In: Hoar W.S. & Randall D.J. (eds), *Fish physiology, Volume XI The physiology of developing fish, Part A Eggs and larvae*, Academic Press, London, pp. 163–251.
- Amelung M. 1982. Auswirkungen gelöster Eisenverbindungen auf die Ei- und Larvalentwicklung von *Salmo gairdneri* (Richardson). *Arch. FischWiss.* 32: 77–87.
- Andersson P. & Nyberg P. 1984. Experiments with brown trout (*Salmo trutta* L.) during spring in mountain streams at low pH and elevated levels of iron, manganese and aluminium. *Rep. Inst. Freshwater Res. Drottningholm* 61: 34–47.
- Audet C., Munger R.S. & Wood C.M. 1988. Long-term sublethal acid exposure in rainbow trout (*Salmo gairdneri*) in soft water: effects on ion exchanges and blood chemistry. *Can. J. Fish. Aquat. Sci.* 45: 1387–1398.
- Bagge P. & Ilus E. 1975. Ferrosulfaatin ja sitä sisältävien jätevesien akuutista myrkyllisyydestä murtovedessä [The acute toxicity of ferrosulphate and ferrosulphate waste waters in brackish water]. *Meri* 3: 46–64. [In Finnish with English summary].
- Baker J.P. & Schofield C.L. 1980. Aluminum toxicity to fish as related to acid precipitation and Adirondack surface water quality. In: Drablos D. & Tollan A. (eds), *Ecological impact of acid precipitation, SNSF-project*, Oslo-Ås, pp. 292–293.
- Beamish R.J., Lockhart W.L., van Loon J.C. & Harvey H.H. 1975. Long-term acidification of a lake and resulting effects on fishes. *Ambio* 4: 98–102.
- Blackstock N. & Pickering A.D. 1982. Changes in the concentration and histochemistry of epidermal mucous cells during the alevin and fry stages of the brown trout *Salmo trutta*. *J. Zool.* 197: 463–471.
- Buhl K.J. & Hamilton S.J. 1991. Relative sensitivity of early life stages of Arctic grayling, coho salmon, and rainbow trout to nine inorganics. *Ecotoxicol. Environ. Safety* 22: 184–197.
- Decker C. & Menendez R. 1974. Acute toxicity of iron and aluminium to brook trout. *Proc. W. Virg. Acad. Sci.* 46: 159–167.
- Geertz-Hansen P. & Rasmussen G. 1994. Influence of ochre and acidification on the survival and hatching of brown trout eggs (*Salmo trutta*). In: Müller R. & Lloyd R. (eds), *Sublethal and chronic effects of pollutants on freshwater fish*. FAO, Fishing news books, University Press, Cambridge, pp. 196–210.
- Grande M., Muniz I.P. & Andersen S. 1978. Relative tolerance of some salmonids to acid waters. *Verh. Internat. Verein. Limnol.* 20: 2076–2084.
- Grippio R.S. & Dunson W.A. 1996a. The body ion loss biomarker. 1. Interactions between trace metals and low pH in reconstituted coal mine-polluted water. *Environ. Toxicol. Chem.* 15: 1955–1963.
- Grippio R.S. & Dunson W.A. 1996b. The body ion loss biomarker. 2. Field validation in coal mine-polluted streams. *Environ. Toxicol. Chem.* 15: 1964–1972.
- Gundersen D.T., Bustaman S., Seim W.K. & Curtis L.R. 1994. pH, hardness, and humic acid influence aluminum toxicity to rainbow trout (*Oncorhynchus mykiss*) in weakly alkaline waters. *Can. J. Fish. Aquat. Sci.* 51: 1345–1355.
- Gunn J.M., McMurtry M.J., Bowlby J.N., Casselman J.M. & Liimatainen V.A. 1987. Survival and growth of stocked lake trout in relation to body size, stocking season, lake acidity, and biomass of competitors. *Trans. Amer. Fish. Soc.* 116: 618–627.
- Gutteridge J.M.C., Quinlan G.J., Clark I. & Halliwell B. 1985. Aluminium salts accelerate peroxidation of membrane lipids stimulated by iron salts. *Biochem. Biophys.*

- Acta* 835: 441–447.
- Heikkinen K. 1990. Transport of organic and inorganic matter in river, brook and peat mining water in the drainage basin of the River Kiiminkijoki. *Aqua Fennica* 20: 143–155.
- Hesthagen T. & Jonsson B. 1998. The relative abundance of brown trout in acidic softwater lakes in relation to water quality in tributary streams. *J. Fish Biol.* 52: 419–429.
- Holtze K.E. & Hutchinson N.J. 1989. Lethality of low pH and Al to early life stages of six fish species inhabiting Precambrian Shield waters in Ontario. *Can. J. Fish. Aquat. Sci.* 46: 1188–1202.
- Hudd R., Hildén M., Urho L., Axell M.-B. & Jäfs L.-A. 1984. Kyrönjoen suisto- ja vaikutusalueen kalatalous-selvitys 1980–1982 [Fishery investigations (in 1980–1982) of the Kyrönjoki River estuary and its influence area in the northern Quark of the Baltic Sea]. *Vesihallitus, Tiedotus* 242 A, 249 pp. [In Finnish with English summary].
- Hughes G.M. 1985. Comparative studies of respiration as a guide to the selection of bio-indicators. *Symp. Biomonitor. State Environ.*, pp. 126–141.
- Hulsman P.F., Powles P.M. & Gunn J.M. 1983. Mortality of walleye eggs and rainbow trout yolk-sac larvae in low-pH waters of the LaCloche Mountain area, Ontario. *Trans. Amer. Fish. Soc.* 112: 580–588.
- Jutila E., Ahvonen A., Laamanen M. & Koskiniemi J. 1998. Adverse impact of forestry on fish and fisheries in stream environments of the Isojoki basin, western Finland. *Boreal Env. Res.* 3: 395–404.
- Keinänen M., Peuranen S., Tigerstedt C. & Vuorinen P.J. 1998. Ion regulation in whitefish (*Coregonus lavaretus* L.) yolk-sac fry exposed to low pH and aluminum at low and moderate ionic strength. *Ecotoxicol. Environ. Safety* 40: 166–172.
- Kukkonen J. 1991. Effects of dissolved organic material in fresh waters on the binding and bioavailability of organic pollutants. Ph.D. Thesis summary. *University of Joensuu Publications* No: 22, 39 pp.
- Kullberg A., Bishop K.H., Hargeby A., Jansson M. & Petersen R.C.Jr. 1993. The ecological significance of dissolved organic carbon in acidified waters. *Ambio* 22: 331–337.
- Kännö S. 1993. Arvoituksellinen harjus. *Kalamies* 4: 10–11.
- Laamanen M., Ahvonen A. & Jutila E. 1994. Metsätalouden toimenpiteiden vaikutus Isojoen vesistön kalastukseen ja tilaan — tiedustelututkimus [Effects of forestry on fish and fishing in the River Isojoki watercourse — questionnaire survey]. *Riista- ja kalatalouden tutkimuslaitos, Kalatutkimuksia - Fiskundersökningar* 86, 49 pp. [In Finnish with English abstract].
- Larson K. & Olsen S. 1950. Ochre suffocation of fish in the river Tim. *Rep. Danish Biol. Sta.* 6: 3–27.
- Lehtonen H. 1976. Tutkimus Kemira Oy:n Porin tehtaiden jätevesien kalataloudellisista vaikutuksista sekä kalataloudellinen tarkkailu- ja hoitosuunnitelma. *Riista- ja kalatalouden tutkimuslaitos, Tiedonantoja* 6, 292 pp.
- Li J., Eysgensteyn J., Lock R.A.C., Viedon P.M., van der Heijden A.J.H., Wendelaar Bonga S.E. & Flik G. 1995. Branchial chloride cells in larvae and juveniles of freshwater tilapia *Oreochromis mossambicus*. *J. Exp. Biol.* 198: 2177–2184.
- Liebmann H. 1960. *Handbuch der Frischwasser- und Abwasserbiologie II*, 1049 pp.
- Loenn B.-E. & Oikari A. 1982. Determination of muscle ions from trout, *Salmo gairdneri*, by a simple wet extraction technique. *Comp. Biochem. Physiol.* 72A: 49–53.
- Lydersen E., Poléo A.B.S., Muniz I.P., Salbu B. & Björnstad H.E. 1990. The effects of naturally occurring high and low molecular weight inorganic and organic species on the yolk-sack larvae of Atlantic salmon (*Salmo salar* L.) exposed to acidic aluminium-rich lake water. *Aquat. Toxicol.* 18: 219–230.
- McDonald D.G., Reader J.P. & Dalziel T.R.K. 1989. The combined effects of pH and trace metals on fish ionoregulation. In: Morris R., Taylor E.W., Brown D.J.A. & Brown J.A. (eds), *Acid toxicity and aquatic animals*, Cambridge University Press, Cambridge, New York, Melbourne, pp. 221–242.
- McDonald D.G. & Wood C.M. 1993. Branchial mechanisms of acclimation to metals in freshwater fish. In: Rankin J.C. & Jensen F.B. (eds), *Fish ecophysiology*, Chapman & Hall, London, pp. 297–321.
- McDonald D.G., Wood C.M., Rhem R.G., Mueller M.E., Mount D.R. & Bergman H.L. 1991. Nature and time course of acclimation to aluminum in juvenile brook trout (*Salvelinus fontinalis*). I. Physiology. *Can. J. Fish. Aquat. Sci.* 48: 2006–2015.
- Mount D.R., Swanson M.J., Breck J.E., Farag A.M. & Bergman H.L. 1990. Responses of brook trout (*Salvelinus fontinalis*) fry to fluctuating acid, aluminum, and low calcium exposure. *Can. J. Fish. Aquat. Sci.* 47: 1623–1630.
- Muniz I.P. & Leivestad H. 1980. Acidification — effects on freshwater fish. In: Drablos D. & Tollan A. (eds), *Ecological impact of acid precipitation. Proceedings of an international conference, Sandefjord, Norway, March 11–14, 1980*, pp. 84–92.
- Myllynen K., Ojutkangas E. & Nikinmaa M. 1997. River water with high iron concentration and low pH causes mortality of lamprey roe and newly hatched larvae. *Ecotoxicol. Environ. Safety* 36: 43–48.
- Neville C.M. 1985. Physiological response of juvenile rainbow trout, *Salmo gairdneri*, to acid and aluminum — prediction of field responses from laboratory data. *Can. J. Fish. Aquat. Sci.* 42: 2004–2019.
- Oulasvirta P. 1990. Effects of acid-iron effluents from a titanium dioxide factory on herring eggs in the Gulf of Bothnia. *Finnish Fish. Res.* 11: 7–15.
- Petersen R.C.Jr., Hargeby A. & Kullberg A. 1987. The biological importance of humic material in acidified waters. A summary of the chemistry, biology and ecotoxicology of aquatic humus in acidified surface waters. *National Swedish Environmental Protection Board, Report* 3388, 147 pp.
- Peuranen S., Vuorinen P.J., Vuorinen M. & Hollender A.

1994. The effects of iron, humic acids and low pH on the gills and physiology of brown trout (*Salmo trutta*). *Ann. Zool. Fennici* 31: 389–396.
- Playle R.C., Goss G.G. & Wood C.M. 1989. Physiological disturbances in rainbow trout (*Salmo gairdneri*) during acid and aluminum exposures in soft water of two calcium concentrations. *Can. J. Zool.* 67: 314–324.
- Poléo A.B.S., Østbye K., Øxnevad S.A., Andersen R.A., Heibo E. & Vøllestad L.A. 1997. Toxicity of acid aluminium-rich water to seven freshwater fish species: A comparative laboratory study. *Environ. Pollut.* 96: 129–139.
- Rask M., Vuorinen M. & Vuorinen P.J. 1988. Whitefish stocking: an alternative in mitigating acidification effects? *Finnish Fish. Res.* 9: 489–495.
- Rask M., Vuorinen P.J., Raitaniemi J., Vuorinen M., Lappalainen A. & Peuranen S. 1992. Whitefish stocking in acidified lakes: ecological and physiological responses. *Hydrobiologia* 243/244: 277–282.
- Rask M., Vuorinen P.J. & Vuorinen M. 1990. Delayed spawning of perch, *Perca fluviatilis* L., in acidified lakes. *J. Fish Biol.* 36: 317–325.
- Reader J.P., Everall N.C., Sayer M.D.J. & Morris R. 1989. The effects of eight trace metals in acid soft water on survival, mineral uptake and skeletal calcium deposition in yolk-sac fry of brown trout, *Salmo trutta* L. *J. Fish Biol.* 35: 187–198.
- Rees R.M. & Ribbens J.C.H. 1995. Relationships between afforestation, water chemistry and fish stocks in an upland catchment in south west Scotland. *Water Air Soil Pollut.* 85: 303–308.
- Reynolds B., Stevens P.A., Adamson J.K., Hughes S. & Roberts J.D. 1992. Effects of clearfelling on stream and soil water aluminium chemistry in three UK forests. *Environ. Pollut.* 77: 157–165.
- Roekens E.J. & van Griegen R.E. 1983. Kinetics of iron(II) oxidation in seawater of various pH. *Mar. Chem.* 13: 195–202.
- Rombough P.J. 1988. Respiratory gas exchange, aerobic metabolism, and effects of hypoxia during early life. In: Hoar W.S. & Randall D.J. (eds), *Fish physiology, Volume XI The physiology of developing fish, Part A Eggs and larvae*. Academic Press, London, pp. 59–161.
- Roy R.L. & Campbell P.G.C. 1997. Decreased toxicity of Al to juvenile Atlantic salmon (*Salmo salar*) in acidic soft water containing natural organic matter: a test of the free-ion model. *Environ. Toxicol. Chem.* 16: 1962–1969.
- SAS Institute Inc. 1988. *SAS/STAT User's Guide, Release 6.03 Edition*. SAS Institute Inc., Cary, NC, 1028 pp.
- Saski E. & Nikinmaa M. 1990. Happaman veden, alumiinin ja raudan vaikutuksesta nahkiaiseen. *Raportti Kokkolan vesi- ja ympäristöpiirille*. Mimeo, 14 pp.
- Smith E.J. & Sykora J.L. 1976. Early development effects of lime-neutralized iron hydroxide suspensions on brook trout and coho salmon. *Trans. Amer. Fish. Soc.* 2: 308–312.
- Smith E.J., Sykora J.L. & Shapiro M.A. 1973. Effect of neutralized iron hydroxide suspensions on survival, growth, and reproduction of the fathead minnow (*Pimephales promelas*). *J. Fish. Res. Board Can.* 30: 1147–1153.
- Stumm W. & Lee G.F. 1960. The chemistry of aqueous iron. *Schweiz. Z. Hydrol.* 22: 295–319.
- Suzuki Y., Kuma K., Kudo I., Hasebe K. & Matsunaga K. 1992. Existence of stable Fe(II) complex in oxalic river water and its determination. *Water Res.* 26: 1421–1424.
- Sykora J.L., Smith E.J. & Synak M. 1972. Effect of lime neutralized iron hydroxide suspensions on juvenile brook trout (*Salvelinus fontinalis*, Mitchell). *Water Res.* 6: 935–950.
- Tam W.H. & Payson P.D. 1986. Effects of chronic exposure to sublethal pH on growth, egg production, and ovulation in brook trout, *Salvelinus fontinalis*. *Can. J. Fish. Aquat. Sci.* 43: 275–280.
- Tuunainen P., Vuorinen P.J., Rask M., Järvenpää T. & Vuorinen M. 1987. Happaman laskeuman vaikutukset kaloihin. Raportti vuodelta 1986 [Effects of acidic deposition on fish. Report 1986]. *Riista- ja kalatalouden tutkimuslaitos, kalantutkimusosasto, Monistettuja julkaisuja* 67, 72 pp. [In Finnish with English summary].
- Tuunainen P., Vuorinen P.J., Rask M., Järvenpää T., Vuorinen M. & Niemelä E. 1990. Happaman laskeuman vaikutukset kaloihin ja rapuihin. Raportti vuodelta 1989 [Effects of acidic deposition on fish and crayfish. Report 1989]. *Riista- ja kalatalouden tutkimuslaitos, Kalatutkimuksia — Fiskundersökningar* 8, 97 pp. [In Finnish with English summary].
- Tuunainen P., Vuorinen P.J., Rask M., Järvenpää T., Vuorinen M., Niemelä E., Lappalainen A., Peuranen S. & Raitaniemi J. 1991. Happaman laskeuman vaikutukset kaloihin ja rapuihin. Loppuraportti [Effects of acidic deposition on fish and crayfish. Final report]. *Suomen Kalatalous* No 57: 1–44. [In Finnish with English abstract].
- Urho L., Hildén M. & Hudd R. 1990. Fish reproduction and the impact of acidification in the Kyrönjoki River estuary in the Baltic Sea. *Environ. Biol. Fish.* 27: 273–283.
- Vuori K.-M. 1995. Direct and indirect effects of iron on river ecosystems. *Ann. Zool. Fennici* 32: 317–329.
- von Lukowicz M. 1976. Der Eisengehalt im Wasser und seine Wirkung auf den Fisch. *Fisch Umwelt* 2: 85–92.
- Vuorinen M., Peuranen S., Nikinmaa M. & Vuorinen P.J. 1995. Na<sup>+</sup> influx in newly hatched fry of pike (*Esox lucius*) and roach (*Rutilus rutilus*) exposed to acidic water and aluminium. In: Saski E. & Saarinen T. (eds), *Environmental Research in Finland Today. Proceedings — Second Finnish Conference of Environmental Sciences, Helsinki, November 16–18, 1995*. *Mikrobiologian julkaisuja* 43/1995, pp. 145–148.
- Vuorinen M., Vuorinen P.J., Hoikka J. & Peuranen S. 1993. Lethal and sublethal threshold values of aluminium and acidity to pike (*Esox lucius*), whitefish (*Coregonus lavaretus pallasii*), pike perch (*Stizostedion lucioperca*) and roach (*Rutilus rutilus*) yolk-sac fry. *Sci. Total Envir.*, Suppl. 1993, pp. 953–967.

- Vuorinen M., Vuorinen P.J., Rask M. & Suomela J. 1994a. The sensitivity to acidity and aluminium of newly-hatched perch (*Perca fluviatilis*) originated from strains from four lakes with different degrees of acidity. In: Müller R. & Lloyd R. (eds), *Sublethal and chronic effects of pollutants on freshwater fish*. FAO, Fishing news books, University Press, Cambridge, pp. 273–282.
- Vuorinen P.J. 1984. Rautaruukki Oy:n Rautuvaaran kaivoksen jätevesien vaikutuksesta taimenen alkionkehitykseen ja poikasiin. Tutkimusraportti. *Riista- ja kalatalouden tutkimuslaitos, kalantutkimusosasto, Monistettuja julkaisuja* 23: 193–206.
- Vuorinen P.J., Rask M., Vuorinen M., Peuranen S. & Raitaniemi J. 1994b. The sensitivity to acidification of pike (*Esox lucius*), whitefish (*Coregonus lavaretus*) and roach (*Rutilus rutilus*): comparison of field and laboratory studies. In: Müller R. & Lloyd R. (eds), *Sublethal and chronic effects of pollutants on freshwater fish*. FAO, Fishing news books, University Press, Cambridge, pp. 283–293.
- Vuorinen P.J. & Vuorinen M. 1991. Effects of long-term prespawning acid/aluminium exposure on whitefish (*Coregonus wartmanni*) reproduction and blood and plasma parameters. *Finnish Fish. Res.* 12: 125–133.
- Vuorinen P.J., Vuorinen M. & Peuranen S. 1990. Long-term exposure of adult whitefish (*Coregonus wartmanni*) to low pH/aluminium: effects on reproduction, growth, blood composition and gills. In: Kauppi P., Anttila P. & Kenttämies K. (eds), *Acidification in Finland*. Springer-Verlag, Berlin, Heidelberg, New York, pp. 941–961.
- Vuorinen P.J., Vuorinen M., Peuranen S., Rask M., Lappalainen A. & Raitaniemi J. 1992. Reproductive status, blood chemistry, gill histology and growth of perch (*Perca fluviatilis*) in three acidic lakes. *Environ. Pollut.* 78: 19–27.
- Waring C.P. & Brown J.A. 1995. Ionoregulatory and respiratory responses of brown trout, *Salmo trutta*, exposed to lethal and sublethal aluminium in acidic soft waters. *Fish Physiol. Biochem.* 14: 81–91.
- Weatherley N.S., Rogers A.P., Goenaga X. & Ormerod S.J. 1990. The survival of early life stages of brown trout (*Salmo trutta* L.) in relation to aluminium speciation in upland Welsh streams. *Aquat. Toxicol.* 17: 213–227.
- Weatherley N.S., Rutt G.P., Thomas S.P. & Ormerod S.J. 1991. Liming acid streams - aluminium toxicity to fish in mixing zones. *Water Air Soil Pollut.* 55: 345–353.
- Weiner G.S., Schreck C.B. & Li H.W. 1986. Effects of low pH on reproduction of rainbow trout. *Trans. Amer. Fish. Soc.* 115: 75–82.
- Wood C.M., McDonald D.G., Ingersoll C.G., Mount D.R., Johannsson O.E., Landsberger S. & Bergman H.L. 1990. Whole body ions of brook trout (*Salvelinus fontinalis*) alevins: responses of yolk-sac and swim-up stages to water acidity, calcium, and aluminum, and recovery effects. *Can. J. Fish. Aquat. Sci.* 47: 1604–1615.

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