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Recovery of young brown trout (*Salmo trutta*) in acidified streams: What are the critical values for acid-neutralizing capacity?

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The recovery of young allopatric brown trout (*Salmo trutta*) grouped into YoY (age 0+) and older parr (age ≥1+) fish, was studied in acid-sensitive streams in a Norwegian watershed during a 24-year-period (1987–2010). Their abundance was assessed by electrofishing. Most sites typically had 5.0–5.5 in pH, 0.4–0.7 mg L^{-1} Ca, 10–20 μg L^{-1} inorganic toxic aluminum (Al_i) and acid-neutralizing capacity adjusted for organic acids (ANC_{OAA}) of - 15 to +25 μeq L^{-1}. Densities of both YoY and older parr increased significantly during the study period. Water quality also improved in recent years with respect to pH (5.8–6.0), Al_i (5–15 μg L^{-1}) and ANC_{OAA} (10–20 μeq L^{-1}). However, some negative trends in both fish density and water chemistry were found during both the first (1987–1993) and last years (2004–2008) of the study. Initially, YoY densities remained at about 16–20 specimens 100 m^{-2} (1987–1990), declined to 10–15 specimens 100 m^{-2} in the early/mid 1990s, and rosed to 30–50 specimens 100 m^{-2} in recent years (1997–2010). Their densities correlated significantly with ANC_{OAA}, and at least three stages in the recovery process were recognised: (i) Low density with 10–20 specimens 100 m^{-2} at −18 to −5 μeq L^{-1}, (ii) medium and unstable density with 20–30 specimens 100 m^{-2} at −5 to 10 μeq L^{-1}, and (iii) increasing density to 40–50 specimens 100 m^{-2} at 10–25 μeq L^{-1}. The decline in brown trout density in the early-mid 1990s coincided with high sea salt depositions, which caused increased acidification. Component 1 in a PCA explained 51% of the variation in fish densities, including conductivity, Mg, Ca, Na, alkalinity and TOC. Component 2 explained an additional 31% of the variation, including pH, Al_i and ANC_{OAA}. Multiple regression analysis coefficients showed that the two components explained 41% of the variance in total fish density. Young brown trout suffered a high mortality during the initial phase of the study in spite of relative low levels of Al_i. This is probabaly because the study streams have very diluted water. The densities of young brown trout have levelled off in recent years, indicating a development towards reaching carrying capacity and hence full recovery. However, still some annual fluctuations in density are recorded, which may be related to an unstable water chemistry.

1. Introduction

Anthropogenic emissions of sulphur and nitrogen oxides have increased the acidity of surface waters in large areas of the world, especially in eastern North America and several European countries (Rodhe et al., 1995). This process has been a major threat to biodiversity in both continents, and has also led to severe fish damage (Tammi et al., 2003; Keller et al., 2007). In Norway, water quality deterioration through acidification has severely impoverished fish communities (Hesthagen et al., 1999a). Nearly 10,000 lake-dwelling populations were extirpated during the 20th century, primarily brown trout (*Salmo trutta*).

A large number of studies have examined the relationship between survival of brown trout and various water chemistry parameters such as pH, inorganic toxic aluminium (Al_i), alkalinity and calcium (McCartney et al., 2003; Alstad et al., 2005; Kroglund et al., 2008; Malcolm et al., 2014). However, acid-neutralizing capacity (ANC) is usually used as a predictive variable in models evaluating the biological effects of acidification (cf. Driscoll et al., 1991; Malcolm et al., 2014). The lower ANC threshold needed to avoid damaged brown trout populations in acidified Norwegian lakes with 95% probability was initially 20 μeq L^{-1}, based on fish status obtained through interviews in 1986 (Bulger et al., 1993; Lien et al., 1996). ANC was at that time calculated as the difference between

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base cations and strong acid anions (*cf*. Reuss and Johnson, 1986). Later, Lydersen et al. (2004) suggested to modify ANC by assuming that the permanent anionic charge of organic acids forms part of the strong acid anions, denoted ANC_{OAA}. Using the 1986-dataset referred showed that no damaged brown trout populations was obtained at ANC_{OAA} of 8 μeq L^{-1} (Lydersen et al., 2004). It should be noted that critical values obtained from traditional ANC and ANC_{OAA} can not be directly compared. Based on a regional survey in 1995, the same protection for brown trout in clear-water lakes was achieved at ANC_{OAA} of 33 μeq L^{-1} (Hesthagen et al., 2008). In this work, probabilities for no damaged brown trout populations were also given for different TOC levels, showing that higher ANC_{OAA} values are needed to protect brown trout in more humic lakes. A higher ANC_{OAA} limit to avoid fish damage in 1995 compared with that in 1986 may be related to increased TOC content during that period (cf. Skjelkvåle et al., 2001). It has been shown that strong organic anions can contribute to the mobilization of Al_i in combination with SO_4^{2-} and NO_3^-, which is an unambiguous indication of effects of acid deposition (Lawrence et al., 2007).

Here, we analyse water chemistry and abundance of young brown trout in acidified streams in a Norwegian watershed throughout a 24-year period, from 1987 to 2010. Since 1980, the content of sulphate in precipitation at a number of sites in Norway fell by 75–91%, and by 54–81% since 1990 (Tørseth et al., 2012). This has led to that surface waters are in recovery, especially since the mid-1990s (Skjelkvåle et al., 2005; Garmo et al., 2014). However, several episodes of sea-salt depositions have occurred during the past 20–25 years, mobilizing more toxic Al (Hindar et al., 1994, 2003). Nevertheless, we expected to find a significant recovery of young brown trout relative to ANC_{OAA} during the study period.

2. Materials and methods

2.1. Study area

The study was performed in the Vikedal watershed in south-western Norway, located about 20 km from the coast (Fig. 1). The watershed covers an area of 119 km^2, which consists mainly of slowly weathering rocks such as granite and gneisses. The study was carried out at eight lakes; Fjellgardsvatn (158 m.a.s.l.), Røyravatn (230 m), Krossvatn (333 m), Djupatjern (366 m), Botnavatn (430 m), Kambetjern (464 m), Flotavatn (587 m) and Risvatn (501 m) (Fig. 1). The brown trout populations in Risvatn and Flotavatn suffered greatly from acidification during the 1980s (Hesthagen and Forseth, 1998). However, other lakes may also have acidified tributary streams with effects on young brown trout. The study sites were located above agricultural land, except for two tributary streams and the outlet of Fjellgardsvatn. None of the other streams sampled were affected by local water pollution, habitat destruction or liming. There are no roads or settlements in the cachment area above Fjellgardsvatn, except for a few small cabins. Brown trout is the only fish species in all the streams studied.

2.2. Fish sampling

Young brown trout were sampled by means of a portable back-pack electrofishing apparatus (1600 V, DC) in late August to early September each year. The water temperature generally ranged between 11 and 14 °C during the sampling. We electrofished most of the inlets, outlets and streams entering each lake. Electrofishing was not carried out above physical obstacles that might prevent brown trout from entering these sections of the streams to spawn. All localities were either sampled from or close to the shore-line of each lake, and always in an upstream direction. In each stream, we established fixed sampling areas that were repeatedly electrofished throughout the study. However, the area sampled in some of the largest inlets or outlets could vary to some extent from year to year, depending on the wetted area. The entire width of each station was generally electrofished, except in the largest inlets and outlets. Sampling station depths generally ranged from 5 to 25 cm, and their mean area ± SD was 71 ± 45 m^2. Between 20 and 24 streams were sampled each year.

The lengths of all captured fish were measured to the nearest mm. Most fish were released after sampling, except for some individuals that were removed for age determination. The fish were classified as either YoY (age 0+) or older parr (age ≥ 1+) on the basis of their length-frequency distribution in each stream. Fish in the two age classes usually ranged from 35 to 65 and 70 to 150 mm in length, respectively (Fig. 2). A total of 12 199 brown trout were caught, of which 80% were YoY (n = 9726). Older parr were mainly one-year-olds. As the sampling was carried out at the latest in early September, only very few mature fish were caught. These specimens were not included in the data-set. Each stream was sampled in a single run during the first six years of the study (1987–1992), and in three successive runs in later years (1993–2010). From the three catches in this last period, we estimated probabilities of capture (p) for both YoY and older parr (cf. Zippin, 1958; Bohlin et al., 1989). The mean p-values for these two age groups were 0.54 ± 0.06 SD and 0.68 ± 0.06 SD, respectively, and these values were used to estimate densities from 1987 to 1992.

We tested whether annual variations in environmental factors influenced the number of fish caught. To do so, we performed multiple regressions with these independent variables each year: (*i*) mean water flow during the sampling period, (*ii*) changes in water flow on days 1, 3 and 5 prior to sampling, compared to that during the sampling period, and (*iii*) water temperature, based on a mean value for all stations each year (cf. Jensen and Johnsen, 1988). The numbers of YoY and older parr caught 100 m^{-2} stream area were treated as dependent variables. Water flow measurements from the main river, River Vikedal, were used as a proxy for our study streams, using data provided by the Norwegian Water and Energy Administration. As our study streams were located in upper reaches of the watershed, data on water flow from the main river may to some extent be biased. The flow record of the river cover the full record of the study. As the variation in water flow during the study was relatively large, we ln-transformed the values for water flow to homogenize the variance of the residuals. The mean water flow (ln WF) during the sampling period each year correlated significantly with the densities of both YoY: $-8.89 * \ln WF + 49.17$, $R^2 = 0.33$, n = 24, t = −3.26, $p = 0.004$, and older parr: $-1.606 * \ln WF + 10.332$, $R^2 = 0.33$ n = 24, t = −3.31, $p = 0.003$. These equations were used to obtain values for correlating the annual catches to annual variations in water flow. This values was derived by estimating the number of fish at a mean water flow during the sampling period each year, divided by corresponding estimates of water flow. We then estimated adjusted annual catches to a mean water flow as the product of the correction value for annual variations in water flow and the original fish catch in each stream. Probabilities of capture were then utilised to estimate separate densities of YoY and older parr in each stream in individual years (Zippin, 1958; Bohlin et al., 1989). Finally, mean density was estimated for both age groups in each year.

2.3. Water chemistry

Water samples were obtained from each stream during the annual electrofishing period. Samples were analysed by standard methods, and parameters included were pH, alkalinity, major ions, conductivity, Tot-P, Si, aluminum (Al) species, total organic carbon (TOC), turbidity and water colour. Cations were