Biomass and number of fish impinged at a nuclear power plant by the Baltic Sea

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Abstract The main aim of this study was to investigate the number and biomass of impinged fish at Forsmark Nuclear Power Plant in Sweden, located on the coast of the Baltic Sea. Of particular interest was the number of impinged individuals of the critically endangered European eel (*Anguilla anguilla*) which is regularly caught in the cooling system. Another aim was to determine the comparability of the results from Forsmark and results from impingement studies in other types of waters. Cross-systems studies make it possible to (1) estimate fish loss at plants where fish is not counted, and (2) to predict changes in fish loss from changes in electricity production or cooling water use. In 2010, 31,300,000 fish with a total biomass of 62,600 kg were impinged at Forsmark. In 2011, 27,300,000 fish weighing 38,500 kg were impinged. The maximum peak in total fish number and biomass occurred in spring. The most critical period for herring was in late summer and early autumn. Regarding eel, the largest impingement losses were recorded in November. The number of fish agreed with earlier established quantities of impinged fish in both freshwater and marine ecosystems. The study also estimated that 1,300 critically endangered eels could survive at Forsmark each year if a fish return system would be constructed to allow the passage of fish from the plant back to the Baltic Sea.

Keywords Fish · Impingement · Nuclear power · Eel

Introduction

Large numbers of fish are impinged and killed in the cooling systems of thermal power plants worldwide (Kelso and Milburn 1979; Greenwood 2008; Azila and Chong 2010). The mortality of fish has been identified as the largest of the potential environmental concerns associated with cooling systems of nuclear power plants in Sweden (Ehlin et al. 2009, 2012). Once-through cooling water circuits take water from ecosystems nearby to control condenser process temperatures and release it back into the same system after use (Kelso and Milburn 1979; Greenwood 2008; King et al. 2010). Of the world's 463 nuclear power reactors, 373 (86 %) use water from natural ecosystems for once-through cooling water circuits and the remaining reactors use other types of cooling (IAEA 2011). In thermal power plants, the number of impinged fish increases by an increasing amount of water required to cool reactor condensers (Kelso and Milburn 1979; Greenwood 2008; Azila and Chong 2010). The cooling water requirement is in turn

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correlated to the electrical effect (MWe) of the reactor (Kelso and Milburn 1979).

The removal of fish by power plants with once-through cooling systems has rarely exerted a demonstrable impact on surrounding fish stock sizes (Madenjian et al. 1986; Barnthouse et al. 2002; Newbold and Iovanna 2007; Greenwood 2008). An exception may be the Diablo Canyon Power Plant in California, USA, which was found to remove about 40 % of the clinid kelpfish larvae during entrainment, thereby affecting the adult population (Ehrler et al. 2002).

This paper concerns fish impingement in the cooling water circuits at the Forsmark Nuclear Power Plant in eastern Sweden (Fig. 1; 60°24′12″N, 18°10′0″E). The aim is to quantify the biomass and number of impinged species, with a focus on dominating species and the European eel (*Anguilla anguilla*). The European eel stock stretches from North Africa to Northern Europe and it spawns in the western Atlantic, in or near the Sargasso Sea. The recruitment of European eel from the Atlantic is estimated to be at a historic minimum (EIFAAC and ICES 2011). The reason may be a combination of factors, such as climate change in the Sargasso Sea, habitat changes on the continents, overfishing, parasites and pollution (Bonhommeau et

al. 2008). European eel is classified "critically endangered" by the IUCN (2012) and because of its poor ecological status, commercial catches of this species have been severely restricted. Recreational fishing of European eel is illegal in Sweden. Unlike Forsmark, at Ringhals Nuclear Power Plant on the west coast of Sweden, impinged fish is diverted back to the sea through a tube connected to a pumping system. The survival rate of European eel is particularly high compared to other species impinged at Ringhals; Andersson et al. (2011) estimated that 86 % of the eel survive the stress caused by the passage. Taft (2000) also stressed that survival rates in fish return systems are highly species-dependent.

In coastal waters surrounding the Forsmark Nuclear Power Plant in Sweden, the heated effluent water from the cooling circuit of the plant has been shown to attract warm water fish species throughout the year (Neuman 1979). The heated effluent at Forsmark has also been related to negative physiological effects hampering fish reproduction (Lukšiené and Sandström 1994; Lukšiené et al. 2000) and egg survival (Sandström et al. 1997).

Impingement studies have been performed in many parts of the world (Ringger 2000; Greenwood 2008; Azila and Chong 2010), although impingement in
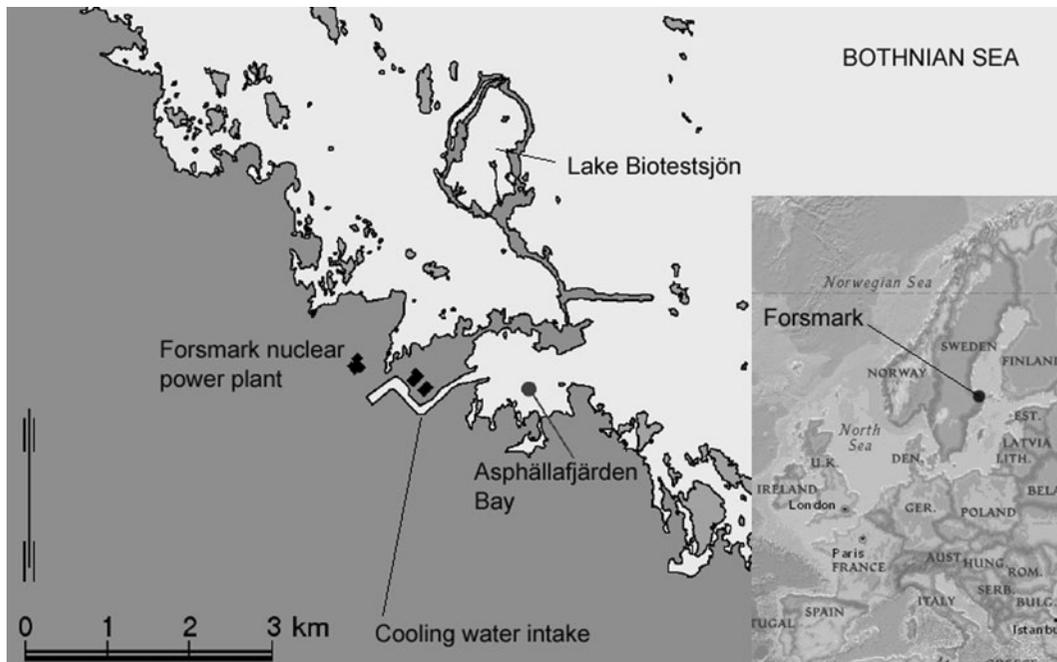

Fig. 1 Forsmark nuclear power plant. Cooling water is taken from Asphällafjärden Bay. Effluent is released into Lake Biotestsjön. The inset (modified from ESRI Base Maps) shows the location of Forsmark in Europe

nuclear power plants around the Baltic Sea has not been covered in the peer-reviewed literature. Moreover, only a few studies (e.g., Kelso and Milburn 1979; Greenwood 2008) have attempted to compare impingement and other cooling system losses across systems. Cross-systems comparisons enable estimation of how much fish is lost at a plant where fish counting is not performed. Such comparisons can also be used to predict effects in fish loss from an increase or decrease in cooling water use of the plant.

In this study, we will determine the comparability of results from the Forsmark area (near a brackish ecosystem) and previously published results (in Kelso and Milburn 1979; Shao and Kuo 1988; Shao et al. 1990; Liao et al. 2004; Greenwood 2008) from plants which use cooling water from freshwater and marine systems, and also elaborate on how impingement studies at various types of aquatic ecosystems can be made more comparable in the future. We will, in addition, assess the extent to which the biomass and number of the impinged fish could change by a proposed increase in cooling water use at Forsmark.

Background and methods

Forsmark Nuclear Power Plant consists of three reactors (F1–F3) which started to operate between 1980 and 1985. The reactor condensers are indirectly cooled by 135 m^3 brackish seawater/s and the flow was constant throughout the measurement period 2010–2011. There are preliminary plans to increase the cooling water use to 170 m^3/s in 2020 as a consequence of a proposed increase in electricity production. The cooling water is led into the plant through a canal from the Asphällafjärden Bay, which is a part of the Bothnian Sea, a sub-basin of the non-tidal estuarine Baltic Sea. The Bothnian Sea is mesotrophic and contains both marine and freshwater fish species. The salinity is approximately 5 psu in Asphällafjärden Bay. Salinity in the Baltic Sea can be considered stationary since the standard deviation of salinity measurements is typically about 5 % of the mean value over the year. A quantitative background description of the Forsmark plant and its surrounding waters is provided in Table 1.

Table 2 compares the background data in Table 1 with data availability in other studies on fish impingement in other thermal power plants. The standard procedure of studies reporting fish impingement in thermal power plants is to publish the amount of cooling water used and the number of impinged fish. In this study, we also included additional data on, e.g., the biomass of impinged fish and minimum mesh size at the innermost filters or screens. The relevance of these data will be discussed in coming sections.

At the Forsmark plant, there were two types of filters used in the sieving station at the time of the study in 2010–2011. The mesh size in the first coarse sieve filter was 40 mm and this filter prevented large organisms and obstacles from passing through. The inner band sieve filters had a mesh size of 2 mm. Filters were cleansed automatically and the material was in general ground in a grinding mill at the plant and used as agricultural fertiliser.

The number and weight of fish trapped in the sieving station were registered once per week throughout of the year for 24 h at the time. During these 24-h periods, all the trapped material was led past the grinding mill and collected. Large objects and other organisms than fish were removed manually. When only fish remained, the total volume of the sample was recorded. Because of the large number of fish impinged, only some representative fish from the sample were counted and classified. First, the entire sample was placed on a sorting table and

Table 1 Background data for the fish investigation at Forsmark nuclear power plant. When applicable, data are specified for the three Forsmark reactors F1, F2 and F3

Data and units	Value
Latitude (°N)	60.4
Period investigated	2010–2011
Cooling water used (m^3/s)	135 (44+44+47)
Electrical effect of power plant (MWe)	3,138 (978+990+1,170)
Thermal effect of power plant (MWt)	9,156 (2,928+2,928+3,300)
Salinity in water (psu)	5.0
Chlorophyll a in water (μg/l)	3.2 (nearest HELCOM monitoring station[a])
Minimum mesh size in filters (mm)	2.0

[a] HELCOM station F64 (60°11′20″N, 19°8′32″E); average long-term concentration June–August

Table 2 Published data in studies on fish impingement at once-through cooling systems of thermal power plants

Plant name	MWt	MWe	Cooling water use	Chl a	N_{fish}	M_{fish}	Minimum screen mesh size	Reference
Forsmark	Yes	Yes	Yes	Yes	Yes	Yes	Yes	This study
Kapar	No	Yes	Yes	No	Yes	Yes	Yes	Azila and Chong (2010)
(15 different)	No	Yes	Yes	No	Yes	Yes	Yes	King et al. (2010)
Longannet	Yes	No	Yes	No	Yes	Yes	Yes	Greenwood (2008)
Doel	No	No	Yes	No	Yes	No	Yes	Maes et al. (2004)
Eems	No	Yes	Yes	No	Yes	No	Yes	Hadderingh and Jager (2002)
Calvert Cliffs	No	Yes	Yes	No	Yes	Yes	Yes	Ringger (2000)
(18 different)	No	No	Yes	No	Yes	No	No	Henderson and Seaby (2000)
Nanticoke	Yes	No	Yes	No	Yes	Yes	No	Wiancko (1981)
(89 different)	No	Yes	Yes	No	Yes	No	No	Kelso and Milburn (1979)
1st NPP	No	Yes	Yes	No	Yes	Yes	Yes	Shao et al. (1990)
2nd NPP	No	Yes	Yes	No	Yes	Yes	Yes	Liao et al. (2004)
3rd NPP	No	Yes	Yes	No	Yes	Yes	Yes	Shao et al. (1990)

MWt thermal effect, MWe electrical effect, $Chl\ a$ chlorophyll a concentration in cooling water, N_{fish} number of impinged fish, M_{fish} biomass of impinged fish, Yes means that data were published, No means that data were not published

divided into two categories: "large fish" (length ≥ 6–8 cm depending on species) and "remaining fish". All the large fish were classified and divided into different containers according to species. The total volume of the remaining small fish was subsequently measured and five 1-l random samples were taken. The next stage of the sorting process included the species determination of the small fish in the five 1-l samples. The weight of each individual from the large fish sample and from the five 1-l samples was recorded, as well as the number and average biomass of individuals from each species. During periods when large fish were particularly numerous, the total volume and total biomass of each species was recorded alongside the biomass of an approximately average size fish from the sample. The fish counting was performed as an integral part of the nuclear power plant's monitoring program (Adill et al. 2012).

To obtain monthly fish impingement values, fish counted at the four or five 24-h periods during each month were considered representative for all days in the month. The number of fish per month was subsequently obtained by summing the total number of fish counted, multiplying by the number of days in each month and dividing by the number of counting periods during the particular month. Monthly fish biomasses were calculated in a corresponding manner.

Herring landings in 2011 were 14,393 kg in the Forsmark area (ICES subdivision 29 N, statistical rectangle 49G8; unpublished data from Havs och Vattenmyndigheten). This information was used to compare with the amount of herring impinged at Forsmark.

Results

The biomass and number of fish impinged at Forsmark in 2010 and 2011 were highly variable between months and seasons (Figs. 2 and 3). Three-spined stickleback dominated both in biomass and numbers during large parts of the investigated period. Exceptions (not visible in Figs. 2 and 3) occurred during August, September and October in 2011, when weekly peaks of herring dominated both in biomass and individual numbers. Smelt dominated the total fish biomass during one week in April, 2010 although three-spined sticklebacks were more numerous than smelt even during this week.

Impingement was greater in 2010 compared to 2011. During 2010, 31,300,000 fish were impinged at the sieving stations. The total biomass of the fish was 62,600 kg, and the average biomass of an impinged fish was 2.0 g. In 2011, 27,300,000 fish were impinged. The total biomass was 38,500 kg and the average individual biomass was 1.4 g. Table 3 gives the percentage of total biomass and total number specified for each of the 33 identified species or species groups during 2010–2011. This table also lists the peak season for species with pronounced seasonal peaks; e.g., herring was primarily impinged during summer and autumn (July–November)

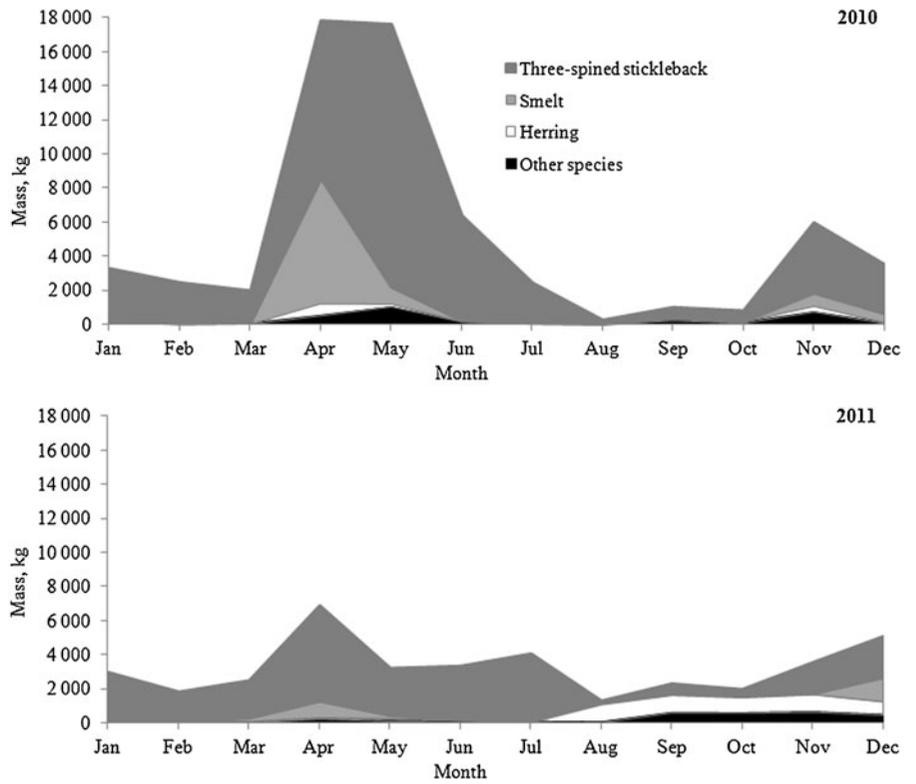Fig. 2 Biomass of impinged fish at Forsmark nuclear power plant 2010–2011

Fig. 3 Number of impinged fish at Forsmark nuclear power plant 2010–2011
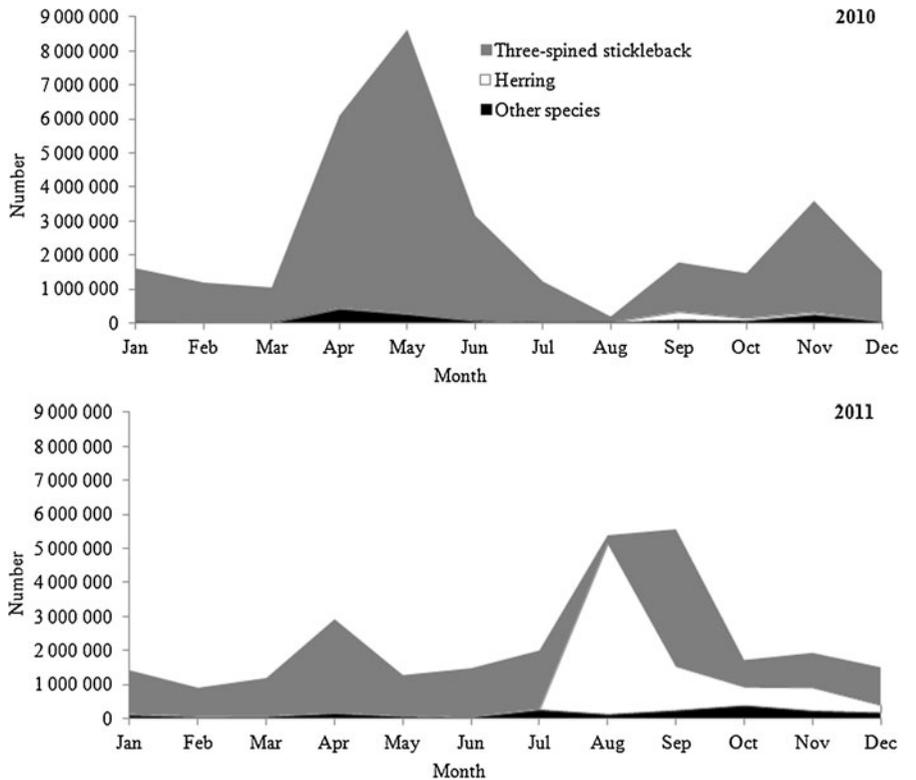
Table 3 Fish species impinged in the once-through cooling water circuit of Forsmark nuclear power plant 2010–2011. Fish counts documented 33 species or species groups. Peak seasons provided for species displaying strong seasonality

| Scientific name	Common name	Percent of total biomass	Percent of total number	Peak season
Gasterosteus aculeatus	Three-spined stickleback	74	79	Spring
Osmerus eperlanus	European smelt	12	0.67	
Clupea harengus	Herring	6.9	15	Summer–autumn
Anguilla anguilla	European eel	2.6	<0.01	Autumn
Pungitius pungitius	Nine-spined stickleback	1.1	3.4	
Perca fluviatilis	Perch	0.6	0.037	
Rutilus rutilus	Roach	0.53	0.028	
Alburnus alburnus	Common bleak	0.51	0.62	
Abramis brama	Common bream	0.46	<0.01	
Gymnocephalus cernuus	Ruffe	0.24	0.015	
Pomatoschistus minutus	Sand goby	0.17	0.68	
Ammodytes	Sandeel	0.097	0.1	
Sander lucioperca	Zander	0.097	<0.01	Summer
Sprattus sprattus	Sprat	0.066	<0.01	Autumn
Triglopsis quadricornis	Fourhorn sculpin	0.065	<0.01	Winter
Nerophis ophidion	Straightnose pipefish	0.057	0.13	
Lampetra fluviatilis	European river lamprey	0.036	<0.01	Winter
Abramis bjoerkna	Silver bream	0.03	<0.01	Spring
Esox lucius	Pike	0.027	<0.01	Summer
Salmo salar	Salmon	0.026	<0.01	Summer
Coregonus maraena	Whitefish (maraene)	0.022	<0.01	
Zoarces viviparus	Viviparous eelpout	0.02	<0.01	
Psetta maxima	Turbot	0.012	<0.01	
Platichthys flesus	European flounder	0.011	<0.01	
Abramis vimba	Vimba bream	<0.01	<0.01	
Carassius carassius	Crucian carp	<0.01	<0.01	
Coregonus albula	Vendace	<0.01	<0.01	
Gadus morhua	Cod	<0.01	<0.01	
Gobius niger	Black goby	<0.01	<0.01	
Liparis liparis	Common seasnail	<0.01	<0.01	
Lota lota	Burbot	<0.01	<0.01	
Spinachia spinachia	Fifteen-spined stickleback	<0.01	<0.01	
Syngnathus typhle	Broadnosed pipefish	<0.01	<0.01	

while silver bream and three-spined stickleback were most common in sieving stations during springtime (March–May).

Figure 2 shows that the minimum fish biomass occurred in August–October during both 2010 and 2011 although there was no corresponding minimum in the number of fish impinged (Fig. 3). A closer look at the data concerning the three dominating species (three-spined stickleback, smelt and herring) revealed

that the average biomass of fish individuals from these species was particularly low in August–October, significantly (at the 95 % confidence level) and approximately one order of magnitude lower than in April.

The impingement of eel (Fig. 4) was greater in 2010 than in 2011. In 2010, 1,943 eels with a total biomass of 1,700 kg (average biomass per individual: 0.87 kg) were impinged at Forsmark compared to 1,166 eels with a total biomass of 950 kg (average

Fig. 4 Number of
impinged European eel
at Forsmark nuclear power
plant 2010–2011. Average
biomass was 0.85 kg
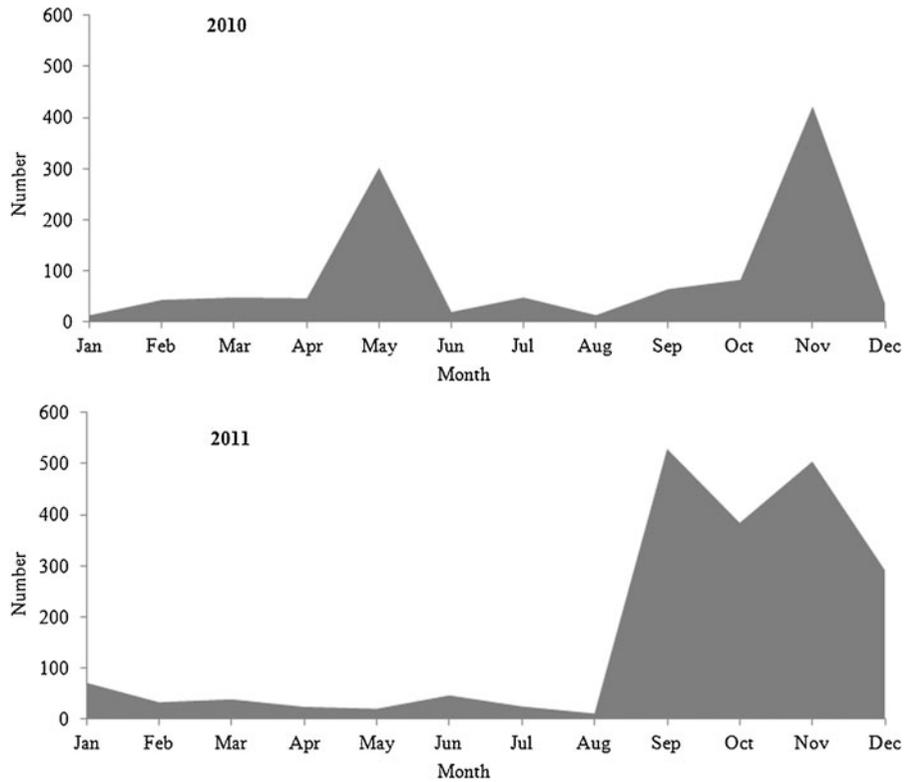
biomass, 0.82 kg) in 2011. If a fish return system would be built at Forsmark, ((1,943 eels+1,166 eels)/2 years)×0.86 [survival rate]=1,300 eels could survive each year, assuming a constant survival rate (86 %) as in Andersson et al. (2011). Impinged herring

weighed 1,662 kg in 2010 and 5,216 kg in 2011. This corresponded to 11.5 and 36.2 % of the herring landings in the Forsmark area in 2011.

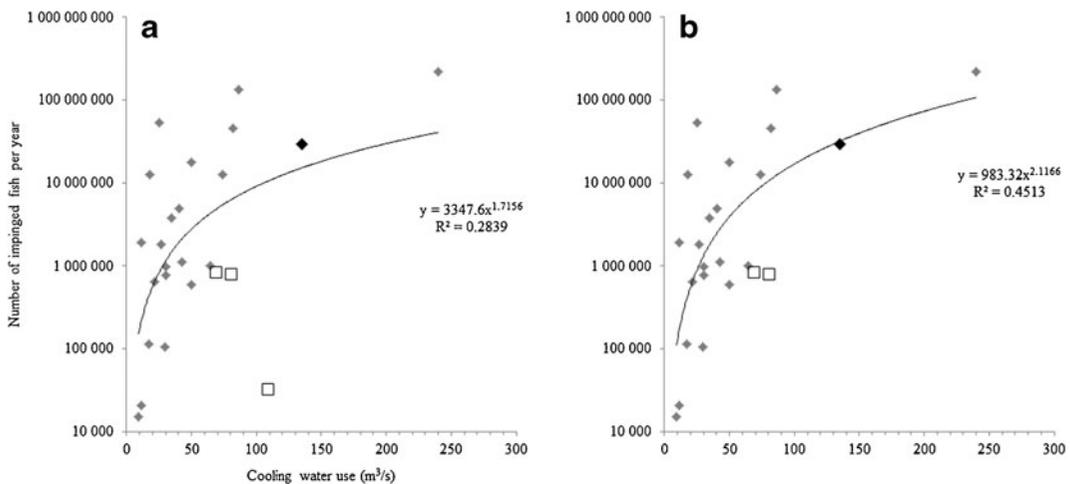Figure 5 relates the Forsmark impingement data to impingement at plants located by tidal coastal waters

Fig. 5 Cooling water use and number of impinged fish in thermal power plants. *Grey dots* represent data from Greenwood (2008) on power plants in NW Europe. The *black dot* represents Forsmark data from the present study. Unfilled squares represent Taiwan's

first, second and, third NPP (data from Shao and Kuo 1988; Shao et al. 1990; Liao et al. 2004). **a** All data included. Number of data: 25; p=0.006. **b** Taiwan's third NPP removed as an outlier. Number of data: 24; p<0.001. The y-axes in both **a** and **b** have log10-scales

in NW Europe (data from Greenwood 2008). The figure also includes mean values from investigations concerning three plants in subtropical and tropical Taiwan (data from Shao and Kuo 1988; Shao et al. 1990; Liao et al. 2004). The Forsmark data fit well into the regression and increased the r^2 value by 1.8 percentage points to 0.535 ($p<0.001$ in both cases; data not shown). However, including data from Taiwan's nuclear power plants (NPP), in particular the third plant, decreased the r^2 value (Fig. 5a; $r^2=0.284$, $p=0.006$). Data from the third NPP concerned an investigation for 24 months and had conspicuously low values. The data point was consequently considered an outlier and was removed from the analysis. This increased the r^2 value considerably to 0.451 ($p<0.001$; Fig. 5b).

Figure 6 compares the total number of fish impinged at Forsmark at a given electrical effect (megawatt electrical; MWe) to impingement at thermal power stations with different electrical effects in the U.S.A. and Canada by the shores of the Great Lakes (from Kelso and Milburn 1979). By adding the brackish water data from Forsmark to this freshwater data set, the r^2 value increased by 2.8 percentage points to 0.576 ($p<0.001$ in both cases; data not shown). Thus, the regression did not show any systematic difference in the MWe-impingement relationship between the

Forsmark data and the freshwater investigation by Kelso and Milburn (1979). When data from Taiwan's first and second NPP were added, the r^2 value decreased slightly to 0.575 ($p<0.001$; Fig. 6). There was no correlation between electrical effect and impinged fish biomass, or between water use and impinged fish biomass at the thermal power plants.

It was not possible to combine Figs. 5 and 6 because the x-axis data were not compatible; cooling water use was not compared to fish impingement by Kelso and Milburn (1979) while MWe was not compared to impingement by Greenwood (2008), although cooling water use and MWe are correlated (Kelso and Milburn 1979). In addition, it was not possible to make any multiple regressions due to data scarcity. There was also no correlation between the minimum mesh size and average mass of impinged fish (data not displayed).

Provided that the minimum mesh size and the mean biomass of individual fish remain, the equation in Fig. 5b could serve as a model to predict some effects from the planned increase in cooling water use at Forsmark, from 135 to 170 m^3/s (an increase by 26 %). According to the equation in Fig. 5b, the number and biomass of impinged fish would then be a factor of $1.26^{2.1116}$ compared to present values, which is equal to an increase by 63 %. This means

Fig. 6 Electrical effect (MWe) and number of impinged fish at thermal power plants. *Grey dots* represent data from Kelso and Milburn (1979) on power plants in the USA or Canada located on the shores of the Great Lakes. The *black dot* represents Forsmark data from the present study. Unfilled squares represent Taiwan's first and second NPP (data from Shao and Kuo 1988; Shao et al. 1990; Liao et al. 2004). Number of data: 41; $p<0.001$. Both axes in the diagram have log10-scales

$$y = 3.1323x^{1.7979}$$
$$R^2 = 0.5751$$
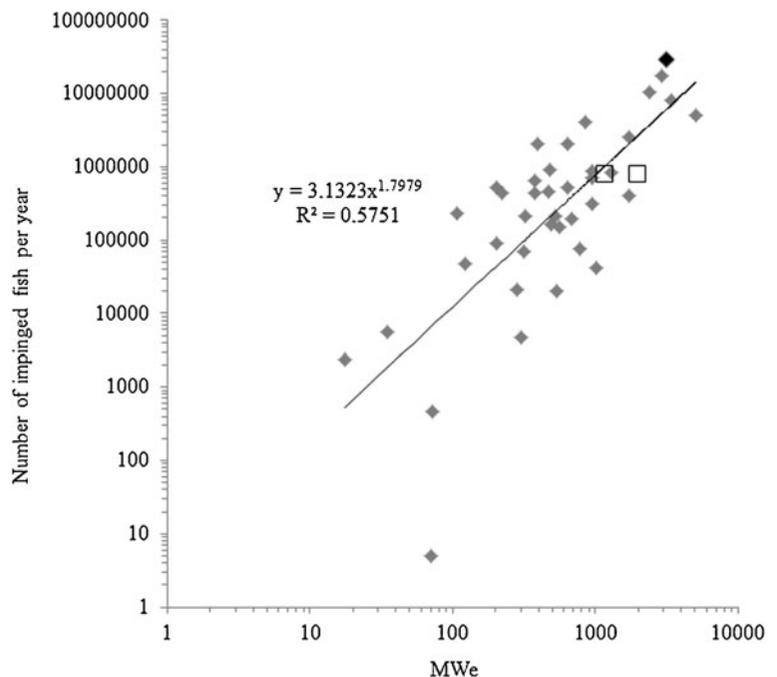
that the number of impinged fish would increase from 29.3 to 47.7 million per year. The biomass would increase from 50.5 to 82.3 metric tonnes per year.

Discussion

Three-spined stickleback dominated the biomass and number of fish impinged at the Forsmark plant in 2010 and 2011 (Figs. 2 and 3, Table 1). This species has also been dominant and increasing in numbers during recent years in a wider range of waters surrounding the Forsmark plant (Karås et al. 2010; Adill et al. 2011). The increase has raised concern since an increasing number of three-spined stickleback may, through an increased competition for zooplankton, hamper the recruitment of larger predatory fish such as pike and perch in coastal waters of the Baltic Sea (Ljunggren et al. 2010). It is therefore possible that the impingement of three-spined stickleback at Forsmark decreases its abundance and is beneficial for pike and perch recruitment by decreasing the predation pressure on zooplankton.

Impinged herring has also caused concern, since herring is a commercially important species in the area and as some of the herring spawns in the vicinity of the Forsmark plant (Adill et al. 2011). Herring impingement in 2011 corresponded to more than 1/3 of the weight of the herring landings in the area (5,216 kg compared to 14,393 kg). It should be stressed that the impinged herrings were mainly juveniles. Although herring in the Bothnian Sea currently are treated as they belong to one single unit in stock assessments, the population structure is not fully determined, particularly with regards to spring and autumn herring in the area. It is therefore unknown whether the impingement of herring may have an effect on the population and this warrants further investigation.

Figures 2 and 3 showed some seasonality and year-to-year difference in impinged fish number and biomass. This means that it is important to monitor impingement frequently in order to acquire representative data. Our data from 2011 are more consistent with earlier impingement investigations by Heibo and Karås (2005; 2 days/week during spring periods 1987–2004 and autumn periods 1986–2003) than with our 2010 data. Heibo and Karås (2005) showed a three-spined stickleback dominance in spring periods 1987–2004 and a herring dominance in autumn periods 1986–2003. Three-spined stickleback and smelt are generally spring-spawners in Sweden and the majority of herring

also spawns during spring in the Baltic Sea (Kullander and Delling 2012). This pattern probably applies also to populations in the Forsmark area (Figs. 2 and 3). The peak in herring number and biomass in August, 2011 (consistent with the pattern in Heibo and Karås 2005) is probably dominated by the young-of-the-year, as indicated by their low individual biomass. European eel abundance tends to peak in August at three sites further south along the Swedish Baltic Sea coast (Svedäng 1996). However, our results suggest that the peak at Forsmark occurs later in the year, around November (Fig. 4). Regarding herring, the most sensitive period to impingement is probably late summer and early autumn (from this study, accounting for results in Heibo and Karås 2005) while the more critical month with regards to eel appeared to be November.

If a fish return system would be built at Forsmark similar to the one at Ringhals Nuclear Power Plant (see "Background and methods"), 1,300 eels per year which presently die at Forsmark could survive according to estimates in this study. There was no attempt made at estimating the economic cost or benefit of building a fish return system at Forsmark, although the current conservation status of the European eel, "critically endangered" (IUCN 2012), should motivate resolute and even costly action directed at saving eel. Autumn investigations of impinged eel at Forsmark reported by Ehlin et al. (2012) indicated an increase in both eel number and biomass between years 1991–2008.

No correlations or trend shifts have hitherto been established between power plant activity and the abundance of any fish species in the Forsmark area. One explanation may be that more investigations are needed, and another may be that compensatory effects related to different competitiveness (e.g., different survival rates or spawning success) at different fish densities may prevent effects from impingement on some or several fish stocks to be distinguished (Henderson et al. 1984; Greenwood 2008). A third reason may be that the effect is too small to measure.

Impingement models can be used to estimate the fish loss at plants where fish is not counted, and also to predict changes in fish loss from changes in plant output or cooling water use. Such models may be uncertain because different geographical regions have different environmental characteristics and different fish communities. Additional explanatory variables could, however, increase the prediction accuracy of impingement models. For instance, a decreasing minimum mesh size in filters

may increase the number of fish caught (Turnpenny 1981). Moreover, the chlorophyll *a* concentration is a common proxy variable for primary production and fish production appears to be proportionate to primary production in lacustrine, estuarine and marine waters (Nixon 1982; Iverson; 1990; Houde and Rutherford 1993; Håkanson and Boulion 2002; Ware and Thomson 2005; Chassot et al. 2007; Jennings and Brander 2010). Minimum mesh size in the innermost filters and chlorophyll *a* concentration could be included in future models as potential additional predictors of the number of impinged fish, although the results from such an inclusion are yet to be shown. Among the 13 studies referred to in Table 2, 10 specify the minimum mesh size and only the present study specifies the chlorophyll *a* concentration. Cooling water use and MWe are correlated at thermal power plants (Kelso and Milburn 1979) but it may nevertheless be beneficial for comparative studies to publish data on both cooling water use and MWe.

No model for investigating relationships governing the biomass of impinged fish at power plants could be developed or tested in this study. Such a model could be useful because other causes of fish mortality (e.g., commercial and recreational fishing) are often quantified and compared in terms of biomass per time unit. We recommend that all data types listed in Table 2 are provided in future studies in order for more accurate and useful models to be developed. Figures 5 and 6 suggest that models can be developed for sites with very different environmental characteristics. The freshwater model from Kelso and Milburn (1979) as well as the model for tide influenced coastal ecosystems from Greenwood (2008) could both be successfully tested using data from the non-tidal estuarine Baltic Sea. However, data from subtropical Taiwan's first and second NPP (Shao and Kuo 1988; Shao et al. 1990; Liao et al. 2004) decreased the r^2 values in Figs. 5 and 6, indicating that there may be a systematic difference compared to temperate ecosystems regarding the impingement loss. This difference may warrant further investigation. The data point representing Taiwan's third NPP in the tropics (data from Shao et al. 1990) was removed as an outlier in Fig. 5 and we believe that this removal was warranted due to a limited investigation time (24 months) with conspicuously low fish impingement numbers. Possibly, future investigations at this plant can determine whether and why data from this site deviate from the patterns in Figs. 5 and 6.

The biomass and number of impinged or entrained invertebrates are currently not monitored at Forsmark, although this may be desirable in the future. Mussel larvae and jellyfish could pose a threat to the functionality of the plant. Entrained crustaceans could decrease the food availability for several fish species (Westin and Aneer 1987) while entrained fish larvae could affect fish reproduction (Kelso and Milburn 1979).

Conclusions

This study investigated the number and biomass of fish impinged during 2010–2011 at Forsmark Nuclear Power Plant located by the Baltic Sea. In 2010, 31,300,000 fish with a total biomass of 62,600 kg were impinged. In 2011, 27,300,000 fish weighing 38,500 kg were impinged. Three-spined stickleback, herring and smelt dominated among the fish. The results were used to test two different regression models for predicting the number of impinged fish using electrical effect and cooling water use, respectively, as predictors. The maximum peak in total fish number and biomass occurred in spring. The most critical period for herring was late summer and early autumn. Regarding eel, the largest impingement losses were recorded in November. If a fish return system would be built at Forsmark, approximately 1,300 critically endangered European eels could be saved annually. Finally, this study predicted that if cooling water use would increase at the Forsmark plant from 135 to 170 m^3/s, both the number and biomass of the fish impinged at the plant would increase by 63 %.

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