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Voluntary angler logbooks reveal long-term changes in a lentic pike, *Esox lucius*, population

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Abstract Sixty-two years of voluntarily collected angling logbook data from a large natural Danish lake were used to study variation in pike, *Esox lucius* L., CPUE (catch per unit effort), expressed as no. of captured pike per boat trip, as an index of stock size. Pike CPUE was positively related to pike release rate by anglers and negatively affected by certain commercial fishers. The stocking of young-of-the-year pike and a fishery-dependent index of perch, *Perca fluviatilis* L., abundance (which may be pike prey or predator depending on size) did not correlate with pike CPUE. Analyses of the size distribution of pike, based on sizes of annual record trophy pike captured by anglers, confirmed the negative impact of commercial pike fishing and revealed a positive influence of air temperature. It is concluded that high-quality angler logbooks that record effort and catch can be a cost-effective tool to inform lake fisheries management by revealing long-term population trends. Further, state space modelling, a statistical technique not yet seen in recreational fisheries science, is recommended as a tool to model proxies for population dynamics from angler logbook data.

KEYWORDS: catch-and-release, commercial fishing, recreational fisheries, state space modelling, stocking, temperature.

Introduction

To study long-term population developments in pike, *Esox lucius* L., and indeed fish in general, researchers can rely on two alternative approaches to data collection: fishery-independent monitoring (e.g. in pike, the Lake Windermere experimental gill-net fishery; Langangen *et al.* 2011) or fishery-dependent data (e.g. using recreational angling records; Lehtonen *et al*. 2009: or commercial catch records; Branch *et al.* 2011). Costs and benefits of these alternative approaches have been extensively discussed (e.g. Hilborn & Walters 1992). In particular, owing to the more random nature of sampling, fishery-independent data may be of higher quality (Branch *et al.* 2011). However, such data are also more costly and are therefore less widespread and often confined to the most valuable fisheries that justify stock assessments. Even then, the treatment of the stock size indices from survey catches will strongly influence inferences drawn from fishery-independent data. Data from Lake Windermere illustrate this effect. While Paxton *et al.* (2009) used a CPUE index of pike recruitment

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from gill nets in their stock–recruitment study (failing to find evidence for female stock size affecting recruitment), reconstructing stock sizes using stock assessment methods in the same data set revealed pronounced Ricker-like stock–recruitment relationships (Edeline *et al.* 2008; Langangen *et al.* 2011). This emphasises that gear biases, such as those associated with gill nets, may strongly affect the quality of the CPUE data to index relative abundance (but see Pierce *et al.* 2010). Such sources of error are potentially more pervasive in non-probability sampling-based fishery-dependent time series, such as those collected using logbooks or diaries. These data may be strongly biased towards more active fishers, who may differentially exploit certain high productivity areas (Pollock *et al.* 1994) or exhibit larger catch rates (Dorow *et al.* 2010).

For many freshwater fisheries where intensive monitoring is logistically and financially impossible (Post *et al.* 2002), diaries or logbooks with self-reporting of catches (and ideally also effort) may be the only realistic opportunity to study long-term trends in fish population changes (Cooke *et al.* 2000; Lehtonen *et al.* 2009; Dorow & Arlinghaus 2011). Data generated using logbooks have successfully been used to explain pike population trends in the Baltic Sea (Lehtonen *et al.* 2009). In the present paper, this logbook approach is extended to the freshwater environment to study long-term trends in angling CPUE of pike from a large Danish lake. The relationship between angling CPUE and changes in harvesting patterns (in particular propensity to catch-and-release in the recreational fishery and commercial fishing activities) and non-fishery influences (e.g. temperature, perch, *Perca fluviatilis* L., abundance) were investigated. Furthermore, angler contest data (annual record pike) were used as a proxy for size structure of the pike population to study impacts of biotic and fishery-related predictor variables on size structure. The data set is rare in length, but not in structure, as self-collected angler logbook data are commonly used by angling clubs in Europe.

Material and methods

Study site

Lake Esrom is mesotrophic, with an area of 17.3 km², maximum depth of 22.3 m and mean depth of 13.5 m. The water volume of the lake is 233×10^6 m³, and the retention time is 12.7 year. The lake is dimictic and stratifies for 3–5 months during summer at 10–15 m depth (Jonasson 2003).

Among the largest lakes in Denmark, Lake Esrom has been the subject of several investigations of ecology and productivity (e.g. Brodersen *et al.* 2001; Jonasson 2003), but unfortunately no regular standardised monitoring has occurred throughout the study period (1949–2010). Hence, data on nutrients such as phosphorous and nitrogen, Secchi depth and water plant colonisation are somewhat fragmented and therefore were not included in the models of pike population dynamics. Lake Esrom has been subject to some anthropogenic influences, but there is no anecdotal evidence that the lake has reached a state of eutrophication that would affect pike spawning and rearing habitats severely, and indeed available data on water clarity show that Secchi depths has been relatively constant over time (Fig. 1). Moreover, although data on water vegetation are scarce, the available data from 1988, 1998, 2001 and 2009 show that water plants are well established in the littoral area (max. depth 6–7 m), and in 2009 water plants covered 12% of the lake area (Müller *et al.* 2010). The fish composition was investigated by standardised gillnet fishing in 1990 and 1997. On both occasions, the fish biomass was dominated by perch, with roach, *Rutillus rutillus* (L.), as a subdominant species. In addition, the lake hosts bream, *Abramis brama* (L.), tench, *Tinca tinca* L., pike, eel, *Anguilla anguilla* L., rudd, *Scardinius erythrophthalmus* (L.), ruffe, *Gymnocephalus cernuus* (L.) and a few trout, *Salmo trutta* L. (Frederiksborg County 1991, 1998).

Population dynamics data obtained from recreational fisheries

Lake Esrom has a long history of recreational fisheries and throughout the last century several angling clubs

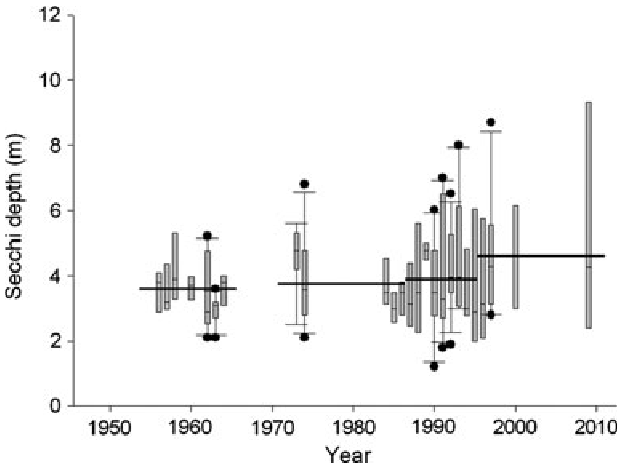

Figure 1. Boxplot of summer secchi depths (May-September) from Lake Esrom. Horizontal lines indicate median values for the respective commercial fisher period (see Table 1). Despite variation between years there was no statistical difference in median Secchi depth between the periods of the different fishers and no commercial fishing (Kruskal–Wallis, $\chi^2 = 5.97$, d.f. = 3, $P = 0.12$).

Table 1. Information on fishing period, focal species and primary fishing gear of the three commercial fishers (A, B & C) fishing on Lake Esrom in the study period (1949–2010)

	Fisher A	Fisher B	Fisher C
Time period	1939–1971	1972–1987	1988–1997
Average annual catches (*t*)	Coarse fish (19.3)	Coarse fish (22.8)	Coarse fish (4.5)
	Eel (11.0)	Eel (13.5)	Eel (4.5)
	Perch (4.7)	Perch (4.5)	Perch (6.0)
	Pike (0.8)	Pike (0.6)	Pike (0.3)
Primary fishing gear	Long lines	Long lines	Long lines
	Fykenet	Fykenet	Fykenet
	Seining	Seining	Pound nets (summer)
		Pound nets (spring and summer)	Trawl
		Trawl	

have been active on the lake. Data from the largest of these angler clubs Lystfiskeriforeningen (LF) are used in this study. LF had between 457 and 703 members (mean 569; SD = 69) during the study period. Angling from the shore of Lake Esrom was not allowed so all angling was done from boats. Since 1940, logbooks have been standardised. Whenever a member intends to fish he/she has to book a boat, and when the member returns in the boat he/she has to register the catch in a special preformatted logbook. Catch registration is mandatory for members of LF, even when the catch is zero. A warning is issued if the logbook is not filled in, and repeated failure to follow the rule results in exclusion from the club; compliance is therefore high.

Based on the angler logbooks the following information has been available on a monthly basis: number of fishing trips (boat trips), number of landed pike and perch per boat trips, number of caught and released pike (catch-and-release estimate) and weights of landed pike and perch per boat trips. A fishing trip is defined as a boat-trip. No further information about the duration of the trip or the number of persons or fishing rods participating exists. However, based on the sizes of the boat it is safe to assume that a maximum of three persons can be actively fishing during the trip with any number of rods. Furthermore, weight of the largest trophy record pike caught per year was available from most years. Exceptions were years where record trophy pike were below 7 kg, as this was the threshold to enter the contest. Hence, in years with no report of record pike, it can be assumed that the record pike was below 7 kg, but no precise weights of record pike were available for those years.

Quantitative analysis was conducted on data from 1949 to 2010; data prior to 1949 were excluded because data were frequently missing and motor boats were not present. Recreational pike fishing on Lake Esrom has traditionally peaked from the end of the closed season (1 May) until the end of July. In August and September, perch gather in large schools in deeper waters and are then subject to a targeted fishery. The fishery is more mixed from October onwards through the rest of the year. Winter fisheries targeted pike in the later years, but in the earlier years all boats were taken out of the water over winter. These patterns are also reflected in the catch compositions. Hence, for the estimation of pike (perch) CPUE, only monthly data from May to July (August to September) were included.

Catch data from commercial fisheries

Since 1730, there have been records of commercial fishing on Lake Esrom. Commercial fishing has always been in the hands of only one person at the time who has rented the fishing rights from the government. During the study period, there have been three different commercial fishers on the lake: A, B and C (Table 1). Each had different fishing behaviours as their primary fishing methods varied, as did their primary focal species (Table 1). Based on anecdotal information, commercial Fisher A was active in terms of ensuring some sustainability in his fishery. Until 1969 he annually stocked 400 000 pike fry and several tonnes of glass eel, *A. anguilla* L. Fisher B fished more intensively than the previous fisher, especially with fykenets and fixed pound nets during spring and summer, and stopped the practise of stocking young pike (Table 1). When Fisher C took on the commercial fishing, the Danish state prohibited commercial fishing for pike in Lake Esrom but the fisher was still allowed to land pike that were caught and injured in the fishing gear as bycatch. As a consequence of the restrictions on commercial pike fishing, the use of some fishing gear and especially pound nets was reduced during the period, and the commercial catch of pike declined accordingly (Table 1). Commercial fishing has been prohibited on the lake since 1998.

Model parameters

Fishery variables Pike population dynamics were evaluated to determine whether they were related to variation in commercial fishing intensity and methods used by specific commercial fishers using the time periods of the three commercial fishers (A,B,C) as well as the period without commercial fishing (period D) as categorical factors (*commercial fisher ID*). This made it possible to evaluate whether there were specific differences in population dynamics among the time periods of the different fishers potentially relating to variability in fisher behaviour such as the gear used, effects of regulation (i.e. commercial fishing by Fisher C was regulated as he was only allowed to harvest pike as bycatch) or fishing intensity for large specimens. The approach also accounted for weaknesses, such as underreporting of landings**.** As commercial fishing for pike took place even after the May to July pike angler fishing period, the period of commercial fishing was delayed by a year, that is, when Fisher C stopped fishing in 1987, 1988 was used as threshold time in the model. Density of stocked pike (*pike stocking*) was also included in the model for CPUE (Table 2) to explore whether pike density increased. A delay in the data was included as the stocking densities 4, 5 and 6 years previous to the focal year was averaged allowing the pike to grow larger than the harvest minimum size of 40 cm. Finally, the average proportion of pike released by anglers the previous 2 years to the focal year was used as an input in the models (*anglers release rate*) to explore whether angler release rates influence pike population dynamics through reducing fishing mortality (Table 2; Fig. 2b).

Biotic variables Being the most dominant species in the lake, small perch was considered a potentially important food for pike and therefore included in the model. Similar to pike, anglers on Lake Esrom also kept logbooks on perch catches. Therefore, $CPUE_{\text{perch}}$ ($N_{\text{monthly sum of numbers caught}}/E_{\text{monthly sum of boat trips}}$) and *perch mean weight* ($W_{\text{monthly sum of kg landed}}/N_{\text{monthly sum of number landed}}$) were used as proxies for perch density and size structure (Fig. 2). Annual estimates were modelled using the state space approach described later for the pike CPUE variable to circumvent occasional months where data were lacking. Recent prey availability for pike was therefore evaluated using $CPUE_{\text{perch}}$ (*perch prey*) averaged for year 1 and 2 previous to the focal year as model inputs (Table 2). Perch can also be a predator on small pike and potentially reduce pike recruitment (Edeline *et al.* 2008; Langangen *et al.* 2011). As a proxy for this, the perch CPUE and size in year 4, 5 and 6 prior to the focal year (*perch predator, perch predator mean weight*) was included in the $CPUE_{\text{pike}}$ start model (Table 2). Because pike populations are cannibalistic and often show density dependent growth (Arlinghaus *et al.* 2009) $CPUE_{pike}$ was included as a variable in the pike record size model.

Abiotic variables It was expected that annual temperature variation could influence recruitment success of pike (e.g. Langangen *et al.* 2011). As water temperature data were not available, air temperature data (monthly average for April to October over the previous 5–9 years) from Copenhagen (approximately 50 km from Lake Esrom) provided by Danish Meteorological Institute (Fig. 2b) was used as a surrogate. This allowed an estimate of year class strength (*year class temperature*) based on a study that showed pike in Lake Esrom grow to 40 cm in length in 4–5 years and that the age distribution of the majority of pike in the catchable size (>40 cm) is composed by age 5–9 pike (Frederiksborg County 1991). Further, the variable *catch period activity* (Table 2) was included, to evaluate whether an increase in temperature resulted in an increase in activity and probability of catch (Kuparinen *et al.* 2010). This temperature variable was included as the annual residual from the mean temperature during the catch period (May to July). Finally, to explore whether temperature in recent years influenced current size distribution a

Table 2. Start models for the GAM models used to evaluate relevant biotic, abiotic and fishery-related variables in relation to pike density (pike CPUE) and size distribution in terms of size of annual record pike

Pike CPUE start models

1. *Pike CPUE ~ month + commercial fisher ID + catch period activity + angler release rate + commercial fisher ID × angler release rate*
2. *Pike CPUE ~ month + commercial fisher ID + catch period activity + year class temperature + commercial fisher ID × year class temperature*
3. *Pike CPUE ~ month + commercial fisher ID + catch period activity + perch prey + commercial fisher ID × perch prey*
4. *Pike CPUE ~ month + commercial fisher ID + catch period activity + pike stocking*
5. *Pike CPUE ~ month + commercial fisher ID + catch period activity + perch predator CPUE + perch predator mean weight + perch predator CPUE × perch predator mean weight*

Pike record size start models

1. *Pike record size ~ commercial fisher ID + catch period activity + angler release rate + commercial fisher ID × angler release rate*
2. *Pike record size ~ commercial fisher ID + catch period activity + growth temperature + commercial fisher ID × growth temperature*
3. *Pike record size ~ commercial fisher ID + catch period activity + perch prey*
4. *Pike record size ~ commercial fisher ID + catch period activity + pike CPUE + commercial fisher ID × pike CPUE*

GAM, General Additive Models.

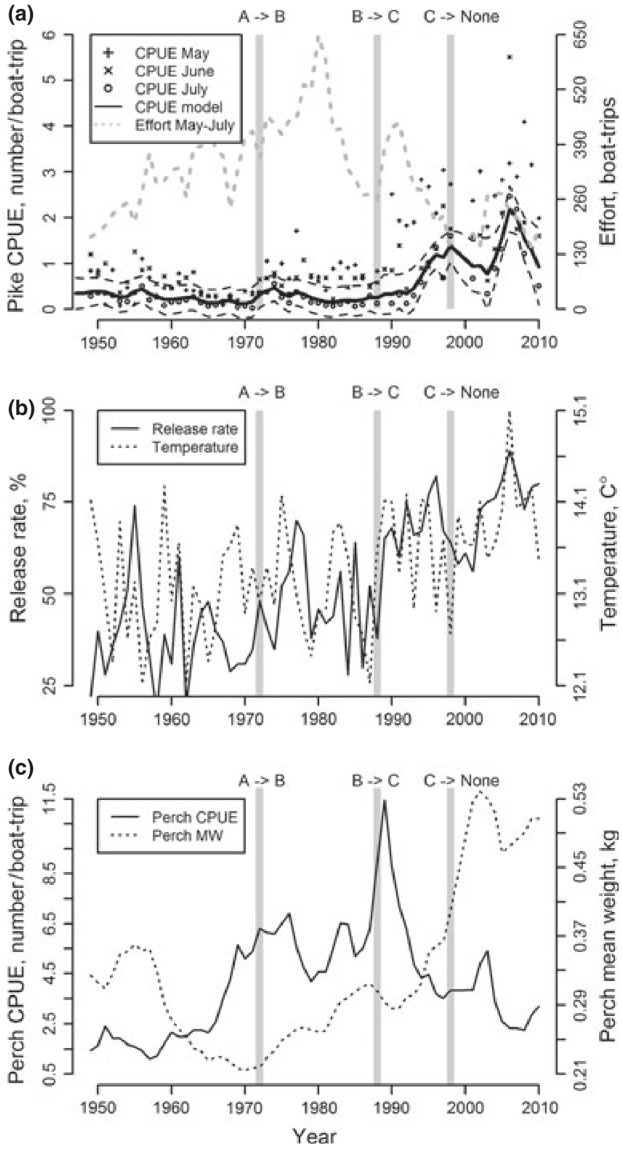

Figure 2. (a) State space model of pike CPUE between 1949 and 2010 based on angler logbooks (solid line 95% CL). Angling effort in sampled angling club in May to July (grey stipled line). Vertical lines indicate transitions between different commercial fishers as well as the period without commercial fishing. (b) Anglers release rate and average summer temperature with no time lag. (c) Perch CPUE and perch mean weight. No time lag.

temperature growth factor was included as the April to October average, averaged over the previous 5 years.

Interaction terms In the CPUE model for pike density the interaction term between *anglers release rate* and *commercial fisher ID* was explored to investigate whether fisher behaviour could play a role in the potential effect of anglers release rate. Likewise, interactions between *year class temperature* and *commercial fisher ID,* and *perch prey* and *commercial fisher ID* were included in the starting models to explore whether the potential role of year class strength and density of perch prey could be influenced by commercial fishing (Table 2). In the trophy record size model, it was explored how temperature influenced pike growth and thereby the size of record pike in combination with commercial fisher ID by including a *temperature growth* × *commercial fisher ID* interaction. Finally, as perch predation on small pike are likely to vary with the size of the perch, a *perch predator* × *perch predator mean weight* interaction was included in the pike CPUE model (Table 2).

State base modelling and angler logbooks

State based modelling is introduced as a new method for modelling angler logbook data. State space modelling assumes that one observation is related to the next. This inter-annual feature can be assumed when modelling population abundance of species such as pike that consist of multiple year classes. Furthermore, such models can combine several data series (here months) and even completely different data types, handle missing data and provide uncertainty estimates (confidence intervals). All this is done in a statistically consistent model that is fitted using maximum likelihood. In the present paper, state space modelling was used to model the predictor variables *perch predator, perch predator mean weight, anglers release rate, perch prey* and *pike CPUE*, the latter only used in the record size model.

State space models assume that the number of fish in a given year is influenced by the number of fish in the previous year.

$$n_{y+1} = n_y \exp(\gamma), \quad \gamma \in N(\mu_n, \sigma_n^2) \tag{1}$$

where n is number of fish in the population, and the relative changes in n from year to year are assumed to be log-normally distributed with location parameter μ_n and scale parameter σ_n.

Under the assumption that CPUE and stock size are correlated, the following relationship between the CPUE or release rate in year y and $y + 1$ holds:

$$CPUE_{y+1} = CPUE_y \exp(\varepsilon), \quad \varepsilon \in N(\mu_{CPUE}, \sigma_{CPUE}^2) \tag{2}$$

This result is equivalent to representing log($CPUE$) as a normally distributed random walk with a mean step μ_{CPUE} and scale parameter σ_{CPUE}. The model was fitted using the random-effects module (Skaug & Fournier 2006) of the AD Model Builder software (http://admb-project.org/).

Briefly, the vector of hyperparameters; here exemplified by the 67 parameters for the pike CPUE, that is based on three series of observations (year y: 1949–2010, month m: 5–7) $\Theta = (\mu_{\mathrm{CPUE}}, \sigma_{\mathrm{CPUE}}, \sigma_{\mathrm{CPUEm5}}, \sigma_{\mathrm{CPUEm6}}, \sigma_{\mathrm{CPUEm7}}, CPUEy_{1949}, \ldots, CPUEy_{1949})$ was estimated by maximising the likelihood.

Data were initially explored by calculating the pairwise correlations between all explanatory variables in each period of commercial fishing. Some of the explanatory variables appeared to be highly correlated (Fig. 2), with Spearman correlation coefficients exceeding the limit of 0.6 (Zuur *et al.* 2009). To avoid violation of the basic assumption of independence, the multivariate analysis was divided into a series of models each analysing independent predictor variables (start models are given in a Table 2). Five and four starting models for the two response variables pike CPUE and pike record size, respectively, were analysed using General Additive Models (GAM) in the R-package ‘mgcv’ (Zuur *et al.* 2009). The data set showed temporal autocorrelation as revealed by inspection of normalised residuals plotted against *year* and Auto Correlation Function plots (not shown). Consequently the GAM model was corrected by accounting for temporal autocorrelation by modelling the correlation structure with an auto-regressive function of Order 1 and including the year as a cubic regression spline smoothed parameter (Zuur *et al.* 2009). Pike CPUE was analysed with catch in numbers as the response variable and log (*effort*) as an offset variable similar to Kuparinen *et al.* (2010). The distribution of catch numbers revealed significant over dispersion (tested using odTest function from the pscl package), and a negative binomial distribution for catch numbers in the GAM models was therefore applied. Pike record size was continuous and well above zero, so a normal distribution was used for this response variable. Because the aim of the study was hypothesis testing of potential explanatory parameters, the model selection was based on *P*-values and *t*-statistics. Insignificant terms were sequentially removed starting with interactions (‘backward’ modelling). After each removal, each of the previously removed terms were re-included one-by-one, to evaluate whether exclusion of other variables have changed the significance of the previously excluded variables. This procedure was continued until all remaining terms in the model remained significant.

Results

Variation in pike density over time

Anglers’ catch of pike per boat trip (CPUE) varied between 0.02 pike in July 1970 and 5.5 in June 2006 (Fig. 2a). The effort of the anglers in the LF club varied during the 62 years and had a peak around 1980 with over 650 boat-days (Fig. 2a). Since then the effort estimated as boat days has gradually declined (Fig. 2a).

Five independent pike CPUE start models were explored. While all found *month* and *commercial fisher ID* to be significant, only one model had an additional significant effect, namely *angler release rate*. The final pike CPUE model models therefore included (1) a significant seasonal effect of decreasing catch rates through the 3 months in the study period, (2) a significant negative effect from the commercial fisheries (*commercial fisher ID*), and (3) a positively significant effect on pike CPUE stemming from *angler release rate* (Table 3).

The variation in pike abundance during the periods of different commercial fishermen is illustrated in Figure 2a. During the period of Fisher A there appeared to be a declining pike population as the angler catch rate index dropped from above 0.5 to around 0.2 pike per boat trip in the late 1960s, subsequently returning to approximately 0.4 fish per boat trip in the last years of Fisher A. In the period of Fisher B, the pike catch index increased in the first years to around 0.5 but thereafter declined and stabilised around 0.15–0.18 pike per boat trip during the 1980s. When Fisher C took over in 1988, commercial fishing for pike was restricted to bycatch removals only, which coincided with an increasing trend in pike CPUE throughout this period as the index rose from about 0.25 to nearly 1.1 pike per boat trip. After the suspension of commercial fishing in 1998, the index increased further with a peak centred around 2006 (2.2 pike per boat trip), followed by a decline in the recent few years.

Although the interaction between *angler release rate* and *commercial fisher ID* was removed from the model, it is noteworthy that it was on the edge of being significant as the *P* value = 0.052 for Fisher A relative to ‘no fishing’ (Fig. 3).

Table 3. Statistics from the final GAM models of pike CPUE

Significant terms	Est.	SE	*P*
Intercept	2.9	0.28	**<0.001**
May	1.2	0.11	**<0.001**
June	0.8	0.11	**<0.001**
Commercial fisher A	−1.3	0.29	0.739
Commercial fisher B	−0.4	0.18	**0.043**
Commercial fisher C	−0.1	0.15	**<0.001**
Anglers release rate	2.0	0.37	**<0.001**

GAM, General Additive Models.
Significant values are in bold.

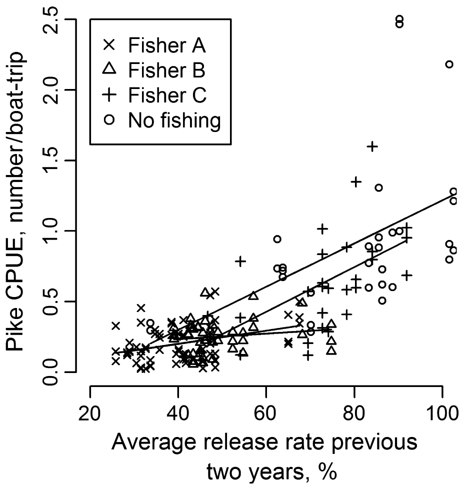

Figure 3. Monthly pike CPUE in Lake Esrom between 1949 and 2010 showing the positive effects of anglers release rate combined with the negative effect of unrestricted commercial pike fishing (Fisher A & B), restricted commercial fishing (Fisher C) and positive effect of no commercial fishing. Pike CPUEs have been corrected for the seasonal catchability effect according to the model by dividing with e^{β}, where β is the parameter estimate for the corresponding month effect. Shifts in Commercial fisher ID (illustrated by point types) have been delayed 1 year to match the model.

Variation in pike record size distribution over time

The record pike size varied through time as the three different commercial fishers exploited the lake (Fig. 4a). The two largest pike (over 13 kg) were caught during the period without commercial fishing. Record pike over 10 kg have been caught regularly through the whole time series, except during the period of Fisher B when only a single pike above 10 kg was captured when accounting for the 1 year time lag on effects (Fig. 4a). During the period without commercial fishing; record pike >10 kg were caught in 8 of 12 years (68%) whereas during the periods of Fishers C and A record pike >10 kg were caught in 40 and 46% of the years, respectively.

All four resulting models included *commercial fisher ID* as a significant variable, with a strong negative effect of commercial fishing – especially from the two fishers that were allowed to target pike (A and B). During the same periods, a significant positive effect of *temperature growth* was found (Table 4, Fig 4b). This effect was not obvious during the period of Fisher C, and the period without commercial fishing.

The following variables were not found to exert any significant relation to pike CPUE or record pike size in any of the nine models explored: *catch period activity, perch prey, perch predator, perch predator mean weight, pike stocking* (including in the pike CPUE starting model only), and *pike CPUE* (included in the record size starting model only).

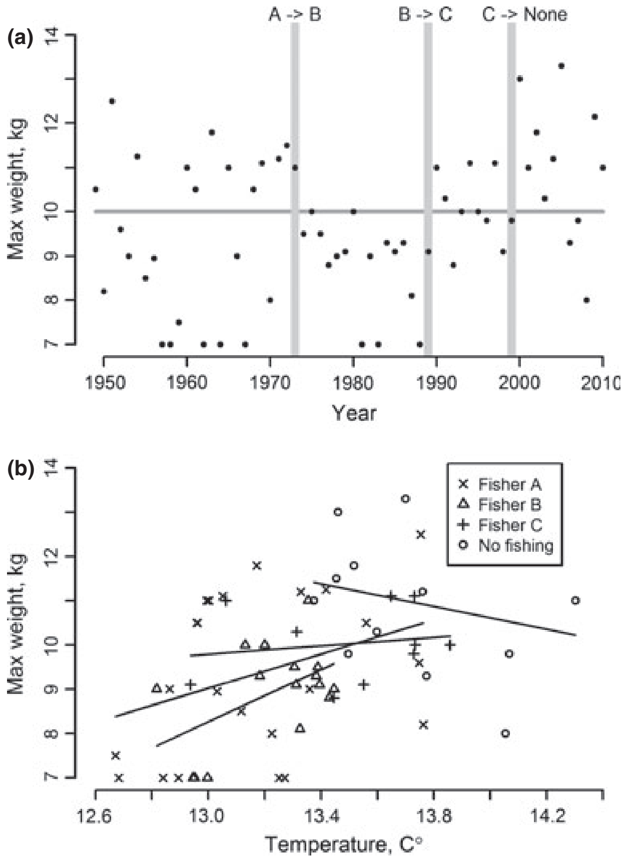

Figure 4. (a) Annual maximum weights of record pike in 1949–2010. Vertical lines indicate transitions between different commercial fishers. The shifts marked by the lines and the IDs marked by point types have been delayed 1 year to match the model input. (b) The effect of temperature on the size of record catch pike illustrated for each of the periods with different commercial fishers. Regression lines represents (from bottom to top) Fisher A, Fisher B, Fisher C and no commercial fishing, respectively.

Discussion

Fishery-related factors

Exploitation of pike populations by anglers and commercial fishers can have a joint impact on densities and size structure (Arlinghaus *et al.* 2010). This was illustrated in the present work by the overall effect of *commercial fisher ID* on both pike CPUE and record pike size, which suggested that individual behaviour and catch strategies of commercial fishers influenced pike population size and trophy fish abundance and corresponding angler catches. The vulnerability of pike to exploitation has been shown in various studies, and in particular size of pike in the stock (and in the catch) is a sensitive indicator of pike overfishing (Pierce *et al.* 1995; Paukert *et al.* 2001; Sharma & Borgstrom 2008; Pierce 2010). In

Table 4. Statistics from the final GAM models of pike record size

Start model		Significant terms	Est.	SE	*P*
2	*Pike record size ~ commercial fisher ID* (*c.f. ID*) + *catch period activity* + *growth temperature* (*gt*) + *interaction* (*c.f. ID – gt*)	Intercept	1.4	0.41	**0.001**
		Commercial fisher A	−1.5	0.70	**0.034**
		Commercial fisher B	−1.9	0.52	**<0.001**
		Commercial fisher C	−1.1	0.40	**0.005**
		Growth temperature	−0.2	0.29	0.403
		Interaction (*C. f. A* × *gt*)	0.8	0.34	**0.019**
		Interaction (*C. f. B* × *gt*)	0.9	0.43	**0.051**
		Interaction (*C. f. C* × *gt*)	0.4	0.36	0.236
1,3,4	*Pike record size ~ commercial fisher ID* + *catch period activity* (see Table 2)	Intercept	1.4	0.41	**0.001**
		Commercial fisher A	−2.2	0.71	**0.003**
		Commercial fisher B	−1.9	0.44	**<0.001**
		Commercial fisher C	−0.9	0.34	**0.014**

GAM, General Additive Models. Start models 1, 3 and 4 (Table 2) all ends with the same result. Abbreviated variables in the start models are *commercial fisher ID* (*C.f. ID*) *and growth temperature* (*gt*) and relevant interactions. Significant values are in bold.

the present study, the vulnerability of pike to recreational fishing was also illustrated by the positive impact of angler's release rate of pike on pike CPUE, supporting modelling studies of recreational fisheries that revealed that releasing pike helps keep abundances and thus catch rates high (Arlinghaus *et al.* 2010). It would have been helpful to calibrate the present model with more precise knowledge of actual fishing mortality rates exerted by commercial and recreational fisheries, but unfortunately there were limitations in the data owing to the potential issue of underreporting in the case of commercial fishing and the incomplete coverage of all anglers on the lake. However, the significant impacts of *commercial fisher ID* and *angler release rate* indicated that fishing mortality affected pike CPUE and size of record pike captured by anglers in the present study.

It is relevant to state that *angler release rate* as a measure of reduced fishing mortality is only valid as long as effort does not substantially increase in conjunction with increased pike stocks and with increased release rates. This is because any substantial increase in effort could imply higher mortality in light of the non-zero hooking mortality probability that characterise pike catch-and-release angling (e.g. Arlinghaus *et al.* 2008). However, in recent years, when release rates increased, angler effort declined, so this should not be an issue. Hence, the positive effect of release rate in this study is very likely due to a reduction in fishing mortality exerted by the anglers on the lake. Therefore, reduced fishing mortality through an elevated catch-and-release fishing of pike, mandatorily or voluntarily, probably increased pike abundance in Lake Esrom. Moreover, as illustrated by the regression lines on Figure 3 and the nearly significant interaction term between *release rate* and *commercial fisher ID* ($P = 0.052$), the greatest effect of angler release rate in the present study was when harvest pressure from commercial fishing was low. This could imply that any positive effects on the pike population owing to release from the anglers might have been suppressed by the commercial fishers. Precise harvest rates from the commercial fishers and the other angling clubs also operating on the lake would have strengthened the conclusion on this aspect, but the presented results still underline why regulation of one sector (e.g. recreational fisheries) needs always to be planned in relation to other impacts, here commercial pike fisheries, to be effective in enhancing the fish stocks.

Another possible explanation of the process behind the almost significant interaction between *angler release rate* and *commercial fisher ID* is based on selection of specific behavioural types by the fishing gear (Biro & Post 2008; Uusi-Heikkilä *et al.* 2008). Fish populations cluster into vulnerable and invulnerable pools (Cox &

Walters 2002). Vulnerability of pike to passive fishing gear such as gill nets and traps is particularly high in spring when fish are active prior to and during spawning time (Casselman 1978). In addition, there are different behavioural types within pike stocks (Jepsen *et al.* 2001; Kobler *et al.* 2009) and some of these fish (e.g. the more active or those less associated with vegetation) are likely to be more vulnerable to angling gear than other behavioural types. It is a plausible scenario that commercial fishers differed in gear types and the timing of their deployment. This could have led to a disproportionably capture of individuals that were also vulnerable to angling, e.g. the more active individuals. In the present case study, Fishers A and B mainly targeted pike during spawning and early spring. Potentially, this could have posed a selection against pike types with behavioural patterns that also rendered these fish highly vulnerable to angling gear. Finally, it should also be recognised that release rates during the periods of Fisher A and B were lower (average 42%) than during the periods of restricted commercial fishing and no commercial fishing (average 70%) introducing the possibility that release rates must exceed a certain threshold level to exert an effect.

Size structure of pike in terms of capture of record pike was also found to correlate with the presence of pike selective commercial fishing on Lake Esrom. In all statistical models examined, the only or most important factor on pike record size structure was *commercial fisher ID*, suggesting that the type of commercial fishing had a strong impact on pike size structure. The negative effects estimated by the model were strongest in the periods of Fishers A and B, the commercial fishers that were allowed to target pike. This is further illustrated by the frequencies of catching a record pike above 10 kg, which were higher after commercial fishing was forbidden on the lake. Moreover, commercial Fisher B seemed to capture a greater fraction of the record sized pike than Fisher A and Fisher C. Fisher B had intensified gear deployment in the shallow littoral areas in spring, compared with the other fishers. Hence, lake managers interested in developing trophy pike fishing may consider managing commercial fishing, and in particular fisheries that target spawning pike. It is well known that trophy pike are very vulnerable to even slight fishing pressure and very protective regulations are needed to avoid substantial size truncation on exploited pike stocks (e.g. Pierce *et al.* 1995; Jolley *et al.* 2008; Arlinghaus *et al.* 2010; Pierce 2010).

A final fishery-dependent factor potentially affecting pike stocks relates to management interventions such as stocking. Stocking of pike was conducted in the lake between 1949 and 1969. At least with the stocking sizes and densities present in this period, the statistical models provided evidence that stocking with young pike did not increase the catchable pike population beyond densities observed in the lake in years when no stocking took place. This is in line with studies suggesting limited or no effects of stocking of young pike whenever natural recruitment takes place (e.g. Grønkjær *et al.* 2004; Skov *et al.* 2011). Other regulations such as altered size limits could not be investigated as there was no variance in the time series. Pierce (2010), however, showed that at high effort levels protection of large pike is only possible when very restricted harvest regulations are employed, and Arlinghaus *et al.* (2010) showed that harvest slot length limits seem to be a useful measure for managing pike stocks.

Abiotic factors

Previous ecological studies on pike population dynamics have often revealed that water temperature exerts a positive influence on pike recruitment and consequently affects pike density (Edeline *et al.* 2008; Paxton *et al.* 2009; Langangen *et al.* 2011). The present study did not support this as *year class temperature* was not retained in any of the CPUE models. This is in line with Lehtonen *et al.* (2009) who did not find a relationship between water temperature and pike CPUE in Baltic sea stocks. However, some support for the role of temperature on pike life history was found in the positive relationship between *growth temperature* and size of the record pike. The mechanism behind this is not straightforward, but could be related to improved growth conditions during periods of warm water. However, it is again remarkable that this relationship varied between the periods of fishers, being most pronounced during the periods of Fisher A and B. Growth of pike could be influenced by density, for example at high densities foraging, and subsequently growth, could be restricted owing to intraspecific competition (Arlinghaus *et al.* 2009) rather than temperature. Hence, at low pike density, which probably was the case during the periods of unrestricted commercial pike fishing (Fisher A and B), temperature increases might have had a stronger effect on growth and therefore on size of record fish. However, because the proxy for water temperature was based on air temperature data from a position several kilometres away, this could have masked some of the biological effect of temperature.

Angler catches in May always exceeded the catch in July resulting in a significant effect of *month* in the CPUE models. This higher catchability of pike in May could be related to lower water temperatures (Kuparinen *et al.* 2010) and/or increased demand to rebuild energy stores after spawning in April and corresponding increased foraging. In addition, during June and July submerged vegetation is normally dense in the shallow areas of the lake making angling difficult in these shallow habitats that pike often prefer.

Biotic factors

The most dominant fish in Lake Esrom is perch. As pike is an opportunistic predator it is likely that perch should be the dominant prey for pike and consequently perch densities should be a proxy for food abundances potentially influencing survival and growth within the pike population similar to the situation in Lake Windermere (Edeline *et al.* 2008). However, neither *perch prey, perch predator* or *perch predator mean weight* were significant in any of the models. This either suggests that perch predation or perch prey is not a significant structuring factor for pike recruitment, and hence, pike CPUE in Lake Esrom or the proxies for perch prey and perch predator collected from angler catch records lacked detail to track this pattern. It is also worth considering that interactions between pike and perch might have been decoupled, for example, during the period of unrestricted commercial fishing for pike and perch (Fisher A and B). Hence, the structuring role of perch might only have been present in recent years with no or restricted commercial fishing resulting in a much shorter time period to evaluate the pike perch interactions properly. Finally, one should also keep in mind that the perch data originated from angler data and thus represented relative large perch that are not easy prey for most pike. This could also mask any straightforward ‘bottom up’ effect of perch as prey.

Vegetation cover and water visibility may also influence pike abundance (Grimm 1994) and individual behaviour (e.g. Andersen *et al.* 2008), and the lack of thorough monitoring of these factors, that is, in terms of Secchi depths, is a limitation of this study. However, based on the data available, Lake Esrom was affected by eutrophication during the study period but this has only resulted in relatively minor changes in water visibility during the period (Fig. 1). Likewise vegetation cover, another important density regulating factor for pike (Grimm 1994), has been fairly constant at least in recent years. These factors are therefore expected to have exerted limited influence on pike stocks during the study peroid.

Constraints and perspectives

Studies have debated the reliability and usefulness of fishery-dependent sampling techniques to index fish abundance (i.e. Branch *et al.* 2011). The present study adds to this body of work by suggesting that angler-generated data, if collected in a standardised manner and with a sufficient level of detail (such as effort data), has the potential to further knowledge on fish population dynamics and the factors impacting on stocks. The study could not confirm all initially expected relationships between pike CPUE and biotic factors (e.g. perch abundance). Nevertheless the logbook data revealed some expected patterns; most pronounced of these was the impact of commercial fishing on pike population size and size structure, which suggests that careful analysis of data from consistently collected angler logbooks can be used to index pike population properties, such as density and size structure. Moreover, this study revealed that state space modelling, a statistical technique not previously applied to angling catch data, is a useful way to model angling log book CPUE time series as proxies for fish population densities. Occasionally, log books can be lost or be unreadable and such missing data points can be estimated in a reliable way by the state space approach.

Most of the limitations in this study relate to the lack of additional variables consistently collected in the study lake, such as total angling effort on the lake, Secchi depth or temperature. Therefore, angler logbook data will reveal its greatest power if collected together with other key parameters.

Despite the general usefulness of high-quality logbook data, a cautious approach is recommended as the use of angler logbooks also will reflect underlying changes in angler behaviour, gear and skills during the study period. In the present study, there is for example anecdotal evidence that anglers have changed behaviour as the average level of release rate in recent years was higher than in the past, concurrent with a decrease in total effort, that is, number of boat trips. Further, it is also known that more specialised anglers are more prone to perform catch-and-release (Arlinghaus *et al.* 2007). Therefore, it could be that the population of anglers on Lake Esrom today is more skilled compared with years ago, which would be an unaccounted factor contributing to an increase in CPUE in recent years unrelated to stock size changes. To circumvent problems with temporal changes in angler behaviour and skills, a future focus could be on designing logbooks that take angler behaviour and angler skills into account and include measures of angler types. Likewise more knowledge on the individual fish, that is, length and weight of each fish, would increase the quality of the logbooks. More specifically, the following information should be obtained in any future logbook data projects: type of angler, effort, size of individual catch, disposition of the catch. These data should be complemented by an independent assessment of total angler use (to estimate total harvest) and any other mortality sources coupled with the most salient abiotic variables of interest to track population dynamics (e.g. vegetation, temperature, prey). If these data are collected routinely (e.g. by angling clubs), time series analyses such as the one employed here might reveal patterns of interest to understand the past and tentatively project the future.

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