INTRODUCTION

The decline of large predatory fish populations is coupled to habitat changes (Donadi et al., 2017; Eriksson et al., 2009). In extreme cases, such a decline may lead to regime shifts that can transform entire lake ecosystems from one state to another (Carpenter, Kitchell & Hodgson, 1985; Carpenter et al., 1987). Large predatory fish provide important ecosystem services to society, not only as a food supply but also due to their recreational value (Cooke et al., 2018). For example, on average 10.5% of the population in industrialised countries participate in recreational angling, and in Scandinavia participation is particularly high and amounts to over 20% in Finland, Norway and Sweden (Arlinghaus & Cooke, 2009; Arlinghaus, Tillner & Bork, 2015). Therefore, knowledge about population sizes of predatory fish is important in a broad context, due to their ecological, recreational and socioeconomic values (Arlinghaus & Cooke, 2009; Craig, 2008; Hickley, 2009), as well as for the management and conservation of these populations (Williams, Nichols & Conroy, 2002).

Recreational anglers are partly responsible for the decline of large predatory fish (Cooke & Cowx, 2004; Hickley, 2009). For example, the recreational catches of pike, *Esox lucius* L., in the five largest lakes and the coastal areas of Sweden exceed the commercial catches (Sandström et al., 2019). Furthermore, both recreational anglers and researchers have reported dramatic reductions in the catches of pike in coastal waters of the Baltic Sea (Andersson et al., 2000; Lehtonen, Leskinen, Selen & Reinikainen, 2009; Ljunggren et al., 2010; Nilsson, Andersson, Karås & Sandström, 2004). These reports have given valuable insights to the status of...
pike populations, although they are at best documented as catch-per-unit-effort. This approach does not provide a comprehensive view on the status of populations. Hence, from a management point of view, there is a need for easy and cost-efficient population size estimates of pike.

To achieve such estimates, a simple method of utilising the data collected by recreational anglers for estimating the population size of pike is presented. An extended journal, kept by recreational anglers, may provide a substantial dataset for research and management. Here, recreational angling is defined as a non-commercial activity, where fish are caught by rod and reel for leisure, photographed, measured and released. However, recreational fishing can be defined differently in other contexts (Arlinghaus & Cooke, 2009). The practice of catch and release is not only a personal standpoint, as it can also be regulated via fisheries management, for instance when there is no limit on how many fish an angler is allowed to catch, but the harvest of fish is not allowed. This type of management implies that fish are caught and released, and hence ideal for capture–recapture studies.

Due to individual patterns of many animal species, individuals can be identified based on their natural markings. For example, tigers may be identified by the size, shape and relative position of their stripes (Karanth, 1995), whereas small cetaceans may be identified based on damage and abrasions on their dorsal fins (Würsig & Jefferson, 1990). Pike, like other animal species, have unique combinations of natural markings enabling the identification of individuals. Pike have a distinct pattern of white spots on a green background with additional markings caused by damages and yellow-brown pigmentation spots that are independent of the white-green pattern. Although Fickling (1982) proposed that individual pike could be identified based on their natural markings, this type of identification has been neglected in capture–recapture studies of pike. Since Fickling’s study, huge progress has been made with camera technology and today taking high-quality photographs is not only possible for many but also common practice.

Spatial capture–recapture (SCR) models give population size estimates in relation to area, to animal movement and to covariates with information about the landscape, the occasion and the individual (Royle, Fuller & Sutherland, 2018). SCR models provide spatially unbiased population size estimates, given that individuals are identified over several occasions in connection with auxiliary geographical information. As such, SCR models estimate the probability of capturing an individual to the distance from a trap (i.e. location of fishing) to its home-range centre. Furthermore, modern SCR models can estimate landscape connectivity by the use of least cost path algorithms (Royle et al., 2018) and thereby estimate encounter probability in relation to any landscape covariates possibly affecting pike movements and encounters, such as vegetation (Eklöv, 1997) or depth (Arlinghaus, Alós, Pieterek & Klefoth, 2017). During recreational angling, it is common for anglers to take photographs of their catches. If anglers additionally note down the time and the location they are angling, including where their catches are made, this information could be integrated into SCR models.

To achieve and maintain viable fish populations, there is a need for new approaches to be developed and implemented (Crane et al., 2015; Jackson et al., 2016). More so, viable fish populations are important for ecosystem integrity and hence an integral part in the monitoring of European surface waters (Birk et al., 2012). The present study is inspired by earlier ideas in fisheries management and methods in the SCR literature. These include the use of anglers to monitor fish populations (Cowx, Fisher, & Broughton, 1986), the use of characteristic marks to identify pike (Fickling, 1982) and the implementation of unstructured spatial sampling (i.e. an opportunistic sampling path in response to local cues) to SCR models (Fuller, Sutherland, Royle & Hare, 2016; Royle, Chandler, Sollmann & Gardner, 2013; Sutherland, Fuller, Royle & Madden, 2018; Thompson, Royle & Garner, 2012). The aim of this study is to raise attention to the potential role of recreational anglers as citizen scientists. Information readily available from standard fishing trips was utilised, such as photographs and length measurements of fish, date and location. These data were incorporated into SCR models and further analysed to obtain population size estimates. The method can open up new ways to utilise the information from recreational anglers participating in citizen science (Dickinson et al., 2012; Dickinson, Zuckerberg & Bonter, 2010). Furthermore, such methods provide essential data for fisheries management leading to improved conservation and management of pike populations through improved and timely population size estimates.

2 | MATERIALS AND METHODS

2.1 | Ethical statement

This study includes two separate parts: recreational angling without a scientific purpose and the analysis of photographs and length measurements of fish with the purpose of estimating population size. The data come from recreational angling, where collecting these data is a common procedure. The Swedish Board of Agriculture concluded about the present study that as the purpose of capturing the fish was not research-based, there is no need nor possibility to get an approval from the ethical committee. Thus, any formal recommendation of obtaining an ethical permit has not been neglected.

2.2 | Study lake

The study area was the small (6.7 ha), shallow (average depth =1.5 m, max depth 3.3 m) and densely vegetated Lake Fastarbysjön in southeast Sweden (59°35′21.2″N 18°23′58.4″E; Figure 1). In addition to pike, the fish community consists of perch Perca fluviatilis L. and five species of cyprinids: rudd Scardinius erythrophthalmus (L.); roach Rutilus rutilus (L.); bream Abramis brama (L.); white bream Abramis bjoerkna (L.); and tench Tinca tinca (L.). The most common plants forming structured habitats for pike are the yellow pond lily, Nuphar lutea (L.), European bur-reed Sparagnum emersum...
Rehmann and different types of bulrush (Typha spp.). In this lake, both the pond lily (large roots) and bulrush form floating island-like structures. The lake has one inlet from a higher lake and one outlet connecting it to a lower lake; both are small, densely overgrown and do not carry water year round. Hence, pike are hindered from migrating in and out from the lake. The landowner regulates the fishing in the lake, and fishing licences are not sold to the public. Thus, it is unlikely that pike were unknowingly harvested during the study period.

2.3 | Size, sex and identification of individuals

All pike were caught by recreational angling from a boat during open water season (no ice fishing). The anglers used a range of lures of different size (7–18 cm), form and colour in an unstructured manner. The recreational anglers took at least one full and one partial (anterior close up) photograph of the left flank of each individual for identification. They also measured the length from the nose to the tip of the tailfin (the fin was not pinched) to the nearest centimetre by a measuring tape. The pike were then quickly released back to the lake. The identification was restricted to large individuals, that were ≥60 cm in length; this is the average length of a female of 4 years or a male of 7 years (Sandström et al., 2019), based on random samples of 500 females and 432 males from Swedish lakes and coastal areas. The ≥60 cm restriction was necessary, since the fish would be identified by their natural markings and such markings on larger fish are likely to undergo fewer changes compared with smaller ones. Furthermore, juvenile fish can have a different, striped pattern, in contrast to the adult patterns with spots (Fickling, 1982). More so, due to the individual’s large size and age, it is likely that most will have reached sexual maturity (Frost & Kipling, 1967) and that they thereby comprise an important part of the lake’s reproducing population. In addition, larger pike are less likely to be killed or eaten by even larger conspecifics, and are perhaps less vulnerable to injuries by recreational angling. In general, the survival of released pike caught by recreational angling is very high (Arlinghaus, Klefoth, Cooke, Gingerich & Suski, 2009; Arlinghaus, Klefoth, Kobler, & Cooke, 2008). Although the sex of the fish was not noted, for pike the female is considerably larger than the male, and therefore, a majority of the individuals caught in the present study were likely females since the majority of randomly sampled pike ≥60 cm are females (Sandström et al., 2019; Wright, 1990). The individual’s size may affect the frequency in which they attack lures of different type and size, and their hunting behaviour as well (Arlinghaus et al., 2008; Eklöv, 1992). Therefore, individuals were divided in two categories of size 60–80 cm and >80 cm, which were allowed to have separate encounter probabilities (see below). For pike >80 cm, the vast majority are females (Sandström et al., 2019; Wright, 1990). Encounter probability based on sex of fish was omitted on behalf of size.

The first step in identifying individual pike was to compare their lengths. The study period covered 562 days, which allowed time for the pike to grow. The greatest average length difference between cohorts of female year classes 4 and above was 64 mm based on random samples of 500 females from Swedish lakes and coastal areas (Sandström et al., 2019). To not wrongfully conclude that pike of different size are different individuals, a great margin was adopted and 15 cm was used as the maximum growth per year when excluding individuals from comparison based on length. Despite expected annual growth, shorter individuals were also compared with longer ones even if the shorter measure was more recent in time. This is to account for possible length measurement errors, because larger
individuals may be more or less humpback-shaped from time to time, whereas smaller individuals are straighter.

Examples of the style of photographs used in this study and the illustration of the photo-identification method are shown in Figure 2. The final identification of individual pike was based on their natural markings: the size; shape; and relative position of the characteristic white spots on green background. In addition, brown-yellow pigmentation spots and possible damages, such as scars and abrasions, were used as additional identifiers. These pigmentation spots, scars and abrasions are independent from the characteristic white and green markings of pike. When several independent marks can be used for identification, they add an extra level of certainty to the identification method (Würsig & Jefferson, 1990). The photographs of pike were scrutinised by one person whom gave each fish an unique ID and sorted the photographs after capture occasion. The photographs were compiled into a document in chronological order; photographs of the same individual were linked for every capture occasion. The correctness of the initial identification was verified by three additional readers with the use of the document.

2.4 Occasions, effective traps and spatial effort

In this study, a fishing occasion was represented by the date the angling was undertaken with a total of 26 occasions. Of these occasions, six were in autumn 2016 (27 October–4 November), 12 occasions in spring 2017 (28 March–14 May), four occasions in autumn 2017 (17 September–29 October) and four occasions in spring 2018 (30 April–12 May). To mitigate the potential bias of recruitment and mortality on population size across the 562-day study period, the period was divided into two sessions: from autumn 2016 to spring 2017 and from autumn 2017 to spring 2018. These sessions were analysed as samples of two independent (stratified) populations.

The sampling procedure during recreational angling takes the form of an unstructured spatial survey. For this type of sampling, the survey path is not predetermined but evolves opportunistically depending on what the anglers experience on a local scale (Royle et al., 2013). Unstructured spatial surveys are a popular tool in wildlife management where sniffer dogs hunt for scat, which is then analysed for DNA to identify individuals and used as spatial encounter histories in SCR models (e.g. Fuller et al., 2016; Sutherland et al., 2018). For unstructured sampling designs, the sampled area is divided into grid cells to create spatially explicit encounter locations, of which the centroid acts as the effective "trap." In this study, 40 imaginary traps were dispersed over the lake area (Figure 1). The locations where the fish were caught were assigned to the nearest trap location, thereby captures per cell is added up for each occasion. As the study lake is small, anglers can fish the whole lake from a boat during one fishing occasion. Hence, traps could be in near proximity to each other and cover the entire lake area maximising both the chance of spatial recaptures and the chance of encountering new individuals (Sun, Fuller & Royle, 2014). Information about occasion-specific trap effort is standard in SCR models. The trap effort is included by supplying information about which traps were visited by the anglers, that is sampled area at each occasion. Not all traps were visited on every occasion, with the lowest number of visits to a trap being 15, the highest 26 and the median number of visits was 22 during the study period.

2.5 Statistical analysis

The R package oSCR (Sutherland, Royle, & Linden, 2017, 2019) was used to model the spatial explicit encounter histories of the pike caught. The data consisted of 39 individuals (i), 40 traps with a retained location (j) and 26 fishing occasions (k). Spatial capture–recapture models relate the spatial distribution of individuals to the spatial distribution of traps. The capture probability depends on the distance from the individual’s home-range centres (si) to the traps (xj). The traps were fully observed, whereas the home-range centres were latent variables to be estimated based on information from the spatial encounters. The encounter probability (pij) of an individual (i) at a trap location (j) was expressed as (Efford, 2004):

\[
p_{ij} = p_0 \exp \left( - \frac{\text{distance} \left( s_i, x_j \right)^2}{2\sigma^2} \right),
\]

where \( p_0 \) is the baseline (intercept) encounter probability and the exponent is the distance covariate with \( \sigma \) as the spatial scale parameter that describes the shape of the decreasing function; \( \sigma \) is a parameter to be estimated. The encounter probability is \( p_0 \) when the trap is in the centre of an individual’s home range.

The distance covariate assumes symmetric home ranges and Euclidean space use, that is pike make equal use of the lake area. As animals, including fish, tend to choose their own habitat, their encounter probabilities do not always decrease according to the encounter model described above. Ignoring this choice of habitat can lead to a negative bias of population size estimates (Sutherland, Fuller & Royle, 2015). To account for the possible bias, asymmetrical (also called ecological) space-use (ASU) models were fitted, which incorporate an additional resistance parameter (Fuller et al., 2016; Sutherland et al., 2015). These models take into account that home ranges are affected by landscape covariates and allow for asymmetrical home ranges. For the ASU models, the landscape consists of discrete pixels (3 x 3 m) that are given a value of resistance: when no resistance exists, animal movements are exactly Euclidean, whereas with resistance, the movements follow a least cost path. For fitting asymmetric space-use models, the R package oSCR implements a path-finding algorithm from gdistance (van Etten, 2017).

Spatial capture-recapture models require an explicit definition of the possible distribution of home-range centres (Royle & Young, 2008), that is the state space. S. For the present study, the state space covered the whole lake area with a regular grid of 10 x 10 m (comprising 668 discrete pixels), and hence, the shoreline is naturally confining the possible home-range centres. Variation in the
baseline encounter probability ($p_{0_{ijk}}$) can be modelled by including covariates ($C$) for occasion ($k$), trap ($j$) and the individual ($i$), according to:

$$
\text{logit} (p_{0_{ijk}}) = \beta_0 + \beta_1 C_{ijk},
$$

where $\beta_0$ and $\beta_1$ are the parameters to be estimated. Occasion-specific covariates of a linear and quadratic term for temperature as well as individual covariates for a behavioural response and pike size were included. The covariates are described more in detail in the next subsection.

As catching fish puts them under stress and may cause injuries (Baktoft et al., 2013), it is highly unlikely the same individual would be caught more than once during the same fishing occasion. Furthermore, as pike can assemble in small areas, the capture of an individual in a trap does not preclude a capture of another individual in the same trap. Thus, there can be multiple captures at the same trap during one occasion. Hence, for the encounter probability, independent multinomial response models were fitted that allow for the catching of multiple individuals at the same trap, but only catching unique individuals once per occasion (Royle et al., 2013; Schmidt, Meier, Sutherland & Royle, 2017).

The SCR models fitted by the R package oSCR use marginal likelihood and can therefore be evaluated and ranked by $\text{AIC}_C$, where the model with the lowest value has the highest predictive power. All possible combinations of covariates resulted in 96 fitted models. From the 96 models, average parameter estimates and their relative variable importance ($\omega+$) were calculated. The cumulative support for each parameter, $\omega+$, was based on the weights of the models in which the parameter was included. Model average estimates were based on model weights from the $\text{AIC}_C$ values (Burnham & Anderson, 2002). All parameters were assumed to be included in all models; this is known as full model averages, where models that did not contain an estimate for a specific parameter were given a parameter estimate of 0. Hence, the full model average provides a shrinkage estimate for parameters with low relative variable importance.

### 2.6 Creating a spatial data frame and covariates

All analyses were carried out in R (R Core Team, 2019). The packages rgdal (Bivand, Keitt & Rowlingson, 2017), raster (Hijmans, 2016) and sp (Bivand, Pebesma & Gomez-Rubio, 2013; Pebesma & Bivand, 2005) were used to process the lake aerial photograph and to create polygons of lake and vegetation boundaries. The lake aerial photograph was accessed through Lantmäteriet (the Swedish mapping, cadastral and land registration authority) as a red-blue-green orthophoto with pixel size of $25 \times 25$ cm. Two landscape covariates were created based on the distance to north shoreline and distance to the emergent vegetation visible in Figure 1 to test whether pike prefer the vicinity of the sun-exposed northern shore or the densely vegetated areas or both. The landscape covariates consist of two rasters covering the whole lake area of pixel size $3 \times 3$ m ($n = 7,466$), with a measure of distance assigned to each pixel (Figure S1). The package waver (Marchand & Gill, 2017) was used to calculate distances of spatial points to polygons.
Several occasion-specific factors (such as temperature, wind speed and days between fishing) may affect the encounters of pike (Arlinghaus et al., 2017; Kuparinen, Klefoth & Arlinghaus, 2010). Fitting all potential covariates that may affect the encounter probability of pike is not feasible because it may render models too complex. Therefore, temperature was chosen as a covariate based on its importance in controlling the metabolic rate of ectotherms (Brown, Gillooly, Allen, Savage & West, 2004) and thus the activity of pike as well. To estimate the effect of occasion-specific temperature on the encounter probability, linear and quadratic covariates of temperature were included in the model. Temperature observations (daily averages) were accessed through the Swedish Meteorological and Hydrological Institute (SMHI) from weather station Stockholm-Arlanda, approximately 27 km from the lake. Temperature was scaled by dividing it by its standard deviation and centred by subtracting it by its mean.

Fishing effort in time was not equal for each occasion and varied between ≈4–8 hr per occasion. Including a covariate of the fishing time per occasion becomes redundant when it has little predictability. For example, during early spring several long occasions of fishing resulted in zero captures, while during early summer, catches were good even during shorter occasions of fishing. Instead of predicting captures by unit of time, the encounter probability was predicted by occasion-specific spatial sampling effort and temperature. However, spatial sampling effort scales with time. More so, catches by recreational angling are subject to extreme temporal variation (Arlinghaus et al., 2017; Kuparinen et al., 2010; Pierce & Tomcko, 2003), and hence, hourly effort is a redundant covariate to include unless occasion-specific sample size is very high or captures are well predicted by a unit of time. Each pike in this study was caught by the same angler, although other anglers were present in the boat on several fishing occasions. Therefore, the number of anglers was not included in the models as an occasion-specific covariate.

In addition to temperature, the number of previous captures for each individual was used as an individual covariate. This covariate tests whether the encounter probability depends on earlier captures, and is therefore a behavioural effect of the individual. If the behavioural effect is positive, but not modelled, the capture probability will be overestimated, and the population size underestimated (Royle et al., 2013). In addition, the effect of individual size on encounter probability was modelled by including a binary covariate with two categories: individuals between 60–80 cm and those >80 cm. This was to test whether different size categories of fish have different encounter probabilities, potentially caused by size selectivity by angling, for example choice of lure size (Arlinghaus et al., 2008), or that small and large pike have different foraging behaviours (Eklöv, 1992).

The population size for the two different strata was estimated, by including a “session” covariate for the density model. The first session consisted of 18 occasions, from autumn 2016 to spring 2017, and the second session consisted of eight occasions, from autumn 2017 to spring 2018. Dividing the data into sessions may avoid potential problems caused by natural changes in the population size during the study period; in effect, some individuals may grow to ≥60 cm or die during the study. The number of possible sessions to include is weighed against the number of recaptures within each session. Here, the choice of two sessions of approximately 7 and 8 months, respectively, was based on the ability to estimate population size reliably in each stratum, that is the time frame had to be extended to contain enough data. Additional and thus shorter time periods, for example dividing the data in two autumn and two spring strata, would have resulted in uncertain estimates. In addition, parameters for the encounter, movement and asymmetric space-use models were averaged over the two sessions.

3 | RESULTS

During the study period (2016–2018), 39 individuals were caught a total of 66 times, with 21 individuals captured once, 10 individuals captured twice, seven individuals captured three times and one individual captured four times. During the first session, 29 unique individuals were caught, 18 once, 10 twice and one three times. During the second session, 21 unique individuals were caught, 17 once and four twice. Length of individual pike ranged from 60 to 114 cm, and their size frequency distribution was half-normal (Figure 3a). There was a high variability in the number of pike captured per fishing occasion, ranging from 1 to 5 captures per occasion (Figure 3b).
occasion, ranging from five occasions with zero pike to one occasion with ten pike (Figure 3b).

Individual pike were identified by their natural markings even up to one and a half years after the first capture. Of the 39 individuals caught in total, 10 had yellow-brown pigmentation spots, 11 had scars and or abrasions, and three had both types of markings. Hence, nearly half (46%) the individuals had at least one type of additional marking. One of the individuals was captured and identified on the first and on the last day of the study period (562 days apart; see Figure 2).

The baseline encounter probability was \( p_{0,\text{intercept}} = -5.69 \) (logit, \( \pm 0.38 \) SE, \( \omega + = 1.0 \)). As expected, the encounter probability of pike was strongly affected by temperature and the linear (logit, \( p_{0,\text{temperature}} = 0.59 \pm 0.20 \) SE, \( \omega + = 1.0 \)) effect of temperature had high predictability on encounter probability and full relative variable importance. The quadratic (logit, \( p_{0,\text{temperature}^2} = -0.13 \pm 0.13 \) SE, \( \omega + = 0.69 \)) term had lower predictability and importance, and suggests a decline in encounter probability at temperatures above 14.7°C (Tables 1 and 2, Figure 4a,b). Furthermore, the two individual covariates behaviour (logit, \( p_{0,\text{behaviour}} = 0.36 \pm 0.60 \) SE, \( \omega + = 0.39 \)) and size (logit, \( p_{0,\text{size}} = -0.16 \pm 0.31 \) SE, \( \omega + = 0.35 \)) of fish had low predictability on the encounter probability (Tables 1 and 2), the behaviour covariate gave weak support for an increased encounter probability if the individual had been caught previously, and the size covariate gave weak support for smaller, 60–80 cm, pike having lower individual encounter probabilities than larger >80 cm pike.

Model selection by AIC\(_C\) showed that models including the landscape resistance covariate “distance to vegetation” (DV) had full support (\( \omega + = 1 \), Tables 1 and 2). The other landscape resistance covariate “distance to north shoreline” (DNS) had also very strong support (\( \omega + = 0.99 \)). Distance to vegetation had a much greater effect on pike space use than distance to north shoreline, with respective log scale coefficients \( \alpha_{2,\text{DV}} = 0.265 (\pm 0.081 \) SE) and \( \alpha_{2,\text{DNS}} = 0.013 (\pm 0.003 \) SE). These results show that pike prefer to move along the vegetated and sun-exposed northern side of the lake when hunting for prey (since each fish was caught when attacking a lure) rather than in the middle of the lake with no vegetation (Figure 5).

The pike population size of the 6.7 ha lake was estimated to 91 individuals (95% CI: 47–134), which gives a density of 13.5 pike/ha (95% CI: 7.0–20.1). In the second session, the estimated population size was nearly the same as in the first, 89 individuals (95% CI: 72–106), and hence weak support for a lower population size (\( \omega + = 0.27 \)).

The estimated spatial scale parameter sigma was estimated to 336.1 m (95% CI: 91.8–530.4) and indicated that pike could potentially move over a much larger area than the study lake. 95% of the movements from an individual’s respective home-range centre, that is the 95% space use were within \( \sqrt{5.99} \cdot 336.1 = 822.5 \) m, where \( \sqrt{5.99} \) is the value of a chi-square distribution with 2 df when \( \alpha = 0.05 \) (Royle, Kerry & Guelat, 2011). However, circular home ranges were unrealistic given the size of lake relative to sigma, and the importance of the landscape covariates DV and DNS. Thanks to the asymmetric space-use model, realistic home ranges can be modelled as a function of distance and landscape covariates. Figure 6 shows predicted home ranges on the state space, exemplified by four of the captured individuals during session one and two.

### 4 | DISCUSSION

The present study demonstrates that simple fishing journal data from anglers can provide valuable data for SCR models to estimate population size of pike. Essentially, only the time and location of angling, as well as photographs and length measurements of the caught fish, were sufficient input data for population size estimation. Given how simple these methods are, most anglers can take part and collect data for monitoring fish populations. As the millions of people that exercise recreational fishing worldwide (Arlinghaus & Cooke, 2009) often also have an interest in conservation of recreational fishery resources (Arlinghaus, 2006; Granek et al., 2008), the possibility for future studies looks promising.

The results suggest that individual pike can be identified by natural markings at least up to one and a half years in between the captures. In addition to the characteristic pattern of white spots on a green background, nearly half of the caught pike had one or more additional markings, such as brown-yellow pigmentation spots or scars and abrasions (Figure 2). The many types of markings simplify identification and make it more reliable (Würsig & Jefferson, 1990). Utilising natural markings also eradicates the need for marking by tags (which includes a physical operation) and relieves fish from unnecessary stress, such as possible infections and algal growth on tags. Taking a photograph of the fish is therefore a more generic and cost-effective method for identifying individual fish for management purposes. Despite these promising results, further research is required to establish the viability of this method for other species of fish, as many fish species do not have such a distinct individual pattern as pike.

One important observation was that the efficiency (or inefficiency) of angling depends strongly on the occasion. The highest catch per fishing occasion was 10 pike, which is more than during the 12 fishing occasions with the lowest number of caught pike in total (Figure 3b). This observation suggests that for capture success of pike, the timing of the fishing occasion is more important than the amount of time spent fishing on a given occasion. According to these results, the catch per fishing effort by recreational angling scales poorly with the population size of pike. This was also shown by Pierce and Tomcko (2003) who found a poor relationship between catch-per-unit-effort during angling and population size of pike.

In this small 6.7-ha lake, without migrating pike, one could argue that traditional capture-recapture methods would be suitable. For example, a closed population model with an individual covariate for the distance from home-range centre to the centroid of the trap array could be sufficient to estimate population size. However, there are some apparent advantages of using SCR instead of traditional CR. An SCR model can relate spatial variation in encounters to landscape covariates, represented in the present study by the distance to north
**Table 1** Parameter estimates and AIC<sub>C</sub> weight rankings of the 48 highest ranked models of a total of 96 models (outputs from all 96 models can be found in the Table S1)

| Encounter | Density | ASU |
|-----------|---------|-----|
| $p_0$ | $T$ | $r^2$ | $\hat{N}$ | $\hat{N}_2$ | Sigma | $\text{DNS}$ | $\text{DV}$ | $\log L$ | $nPar$ | $\text{AIC}$ | $\text{dAIC}$ | $\text{Weight}$ | CumWt |
| 1 | -5.68 | 0.66 | -0.19 | 87.22 | 5.79 | 0.01 | 0.25 | 321.65 | 7 | 659.31 | 0 | 0.19 | 0.19 |
| 2 | -5.79 | 0.66 | -0.2 | 91.6 | 5.86 | 0.01 | 0.26 | 321.07 | 8 | 660.15 | 0.84 | 0.13 | 0.32 |
| 3 | -5.47 | 0.66 | -0.19 | -0.44 | 90.45 | 5.8 | 0.01 | 0.25 | 321.27 | 8 | 660.54 | 1.23 | 0.1 | 0.43 |
| 4 | -5.81 | 0.44 | - | - | 86.58 | 5.8 | 0.01 | 0.25 | 323.46 | 6 | 660.91 | 1.6 | 0.09 | 0.51 |
| 5 | -5.68 | 0.66 | -0.19 | - | 88.25 | 85.27 | 5.79 | 0.01 | 0.25 | 321.65 | 8 | 661.3 | 1.6 | 0.09 | 0.51 |
| 6 | -5.57 | 0.66 | -0.19 | -0.45 | 95.29 | 5.86 | 0.01 | 0.26 | 320.68 | 9 | 661.35 | 2.04 | 0.07 | 0.65 |
| 7 | -5.71 | 0.44 | - | 0.9 | 90.9 | 5.86 | 0.01 | 0.26 | 322.91 | 7 | 661.83 | 2.52 | 0.05 | 0.71 |
| 8 | -5.59 | 0.45 | - | -0.44 | 89.87 | 5.8 | 0.01 | 0.26 | 323.07 | 7 | 662.13 | 2.82 | 0.05 | 0.76 |
| 9 | -5.79 | 0.66 | -0.19 | -0.44 | 92.41 | 90.13 | 5.47 | 0.01 | 0.25 | 323.84 | 6 | 662.14 | 2.83 | 0.05 | 0.76 |
| 10 | -5.47 | 0.66 | -0.19 | -0.44 | 91.59 | 80.85 | 5.8 | 0.01 | 0.25 | 321.26 | 8 | 662.14 | 2.83 | 0.05 | 0.76 |
| 11 | -5.81 | 0.46 | - | - | 90.19 | 83.69 | 5.8 | 0.01 | 0.25 | 324.65 | 8 | 662.14 | 2.83 | 0.05 | 0.76 |
| 12 | -5.69 | 0.44 | - | -0.45 | 94.62 | 5.86 | 0.01 | 0.26 | 322.51 | 8 | 662.14 | 2.83 | 0.05 | 0.76 |
| 13 | -5.57 | 0.66 | -0.19 | -0.45 | 96.16 | 93.72 | 5.86 | 0.01 | 0.26 | 320.47 | 9 | 662.14 | 2.83 | 0.05 | 0.76 |
| 14 | -5.91 | 0.46 | - | 0.89 | 94.35 | 85.24 | 5.86 | 0.01 | 0.26 | 322.86 | 8 | 662.14 | 2.83 | 0.05 | 0.76 |
| 15 | -5.6 | 0.47 | - | -0.43 | 93.54 | 83.69 | 5.81 | 0.01 | 0.26 | 323 | 8 | 662.14 | 2.83 | 0.05 | 0.76 |
| 16 | -5.69 | 0.46 | - | -0.45 | 98.29 | 88.64 | 5.87 | 0.01 | 0.26 | 322.46 | 9 | 662.14 | 2.83 | 0.05 | 0.76 |
| 17 | -5.72 | 0.66 | -0.19 | - | 90.92 | 5.47 | 0.01 | 0.26 | 326.91 | 6 | 662.14 | 2.83 | 0.05 | 0.76 |
| 18 | -5.83 | 0.66 | -0.2 | -0.47 | 95.86 | 5.38 | 0.01 | 0.26 | 326.31 | 7 | 662.14 | 2.83 | 0.05 | 0.76 |
| 19 | -5.48 | 0.66 | -0.19 | -0.47 | 94.59 | 5.47 | 0.01 | 0.26 | 326.45 | 7 | 662.14 | 2.83 | 0.05 | 0.76 |
| 20 | -5.85 | 0.44 | - | - | 90.34 | 5.47 | 0.01 | 0.26 | 328.72 | 5 | 662.14 | 2.83 | 0.05 | 0.76 |
| 21 | -5.59 | 0.66 | -0.2 | -0.48 | 100.01 | 5.53 | 0.01 | 0.26 | 325.83 | 8 | 662.14 | 2.83 | 0.05 | 0.76 |
| 22 | -5.72 | 0.66 | -0.19 | - | 91.29 | 88.72 | 5.47 | 0.01 | 0.26 | 329.66 | 6 | 662.14 | 2.83 | 0.05 | 0.76 |
| 23 | -5.96 | 0.44 | - | 0.92 | 95.17 | 5.53 | 0.01 | 0.26 | 328.15 | 6 | 662.14 | 2.83 | 0.05 | 0.76 |
| 24 | -5.61 | 0.44 | - | -0.48 | 94.01 | 5.48 | 0.01 | 0.26 | 328.26 | 6 | 662.14 | 2.83 | 0.05 | 0.76 |
| 25 | -5.71 | - | - | - | 90.3 | 5.77 | 0.01 | 0.25 | 329.28 | 5 | 662.14 | 2.83 | 0.05 | 0.76 |
| 26 | -5.83 | 0.66 | -0.19 | 0.95 | 96.83 | 94.13 | 5.53 | 0.01 | 0.25 | 326.3 | 8 | 662.14 | 2.83 | 0.05 | 0.76 |
| 27 | -5.48 | 0.66 | -0.19 | -0.47 | 95.92 | 92.27 | 5.47 | 0.01 | 0.25 | 326.44 | 8 | 662.14 | 2.83 | 0.05 | 0.76 |
| 28 | -5.85 | 0.46 | - | - | 94.19 | 84.27 | 5.47 | 0.01 | 0.25 | 328.66 | 6 | 662.14 | 2.83 | 0.05 | 0.76 |
| 29 | -5.72 | 0.44 | - | -0.49 | 99.35 | 5.53 | 0.01 | 0.25 | 327.67 | 7 | 662.14 | 2.83 | 0.05 | 0.76 |
| 30 | -5.82 | - | - | 0.91 | 94.66 | 5.84 | 0.01 | 0.26 | 328.72 | 6 | 662.14 | 2.83 | 0.05 | 0.76 |
| 31 | -5.75 | - | - | - | 82.87 | 110.06 | 5.78 | 0.01 | 0.25 | 328.81 | 6 | 662.14 | 2.83 | 0.05 | 0.76 |
| Encounter | Density | ASU |
|-----------|---------|-----|
| p₀ | T | T² | Size | Behav | N̂ | N̂₂ | Sigma | DNS | DV | logL | nPar | AIC | dAIC | Weight | CumWt |
| 32 | −5.59 | 0.66 | −0.19 | −0.48 | 0.96 | 101.04 | 98.15 | 5.53 | − | 0.92 | 325.83 | 9 | 671.65 | 12.35 | 0 | 1 |
| 33 | −5.51 | − | − | −0.42 | − | 93.4 | − | 5.77 | 0.01 | 0.25 | 328.95 | 6 | 671.9 | 12.59 | 0 | 1 |
| 34 | −5.96 | 0.46 | − | − | 0.92 | 98.85 | 89.16 | 5.53 | − | 0.93 | 328.1 | 7 | 672.2 | 12.89 | 0 | 1 |
| 35 | −5.61 | 0.47 | − | −0.48 | − | 98.06 | 87.61 | 5.48 | − | 0.91 | 328.19 | 7 | 672.38 | 13.07 | 0 | 1 |
| 36 | −5.86 | − | − | − | 0.95 | 86.87 | 116.8 | 5.84 | 0.01 | 0.26 | 328.21 | 7 | 672.43 | 13.12 | 0 | 1 |
| 37 | −5.62 | − | − | −0.41 | 0.91 | 98.07 | − | 5.84 | 0.01 | 0.26 | 328.39 | 7 | 672.77 | 13.46 | 0 | 1 |
| 38 | −5.56 | − | − | −0.41 | − | 85.79 | 114.16 | 5.78 | 0.01 | 0.25 | 328.47 | 7 | 672.94 | 13.64 | 0 | 1 |
| 39 | −5.72 | 0.46 | − | −0.49 | 0.93 | 103.26 | 92.98 | 5.53 | − | 0.93 | 327.62 | 8 | 673.24 | 13.93 | 0 | 1 |
| 40 | −5.67 | − | − | −0.41 | 0.95 | 90.01 | 121.3 | 5.84 | 0.01 | 0.26 | 327.87 | 8 | 673.73 | 14.42 | 0 | 1 |
| 41 | −5.75 | − | − | − | − | 94.9 | − | 5.45 | − | 0.91 | 334.48 | 4 | 678.96 | 19.65 | 0 | 1 |
| 42 | −5.86 | − | − | − | 0.93 | 98.88 | − | 5.5 | − | 0.92 | 333.91 | 5 | 679.81 | 20.5 | 0 | 1 |
| 43 | −5.79 | − | − | − | − | 86.68 | 113.88 | 5.45 | − | 0.91 | 334.04 | 5 | 680.09 | 20.78 | 0 | 1 |
| 44 | −5.54 | − | −0.44 | − | 97.49 | − | 5.45 | − | 0.91 | 334.06 | 5 | 680.13 | 20.82 | 0 | 1 |
| 45 | −5.91 | − | − | − | 0.97 | 91.02 | 121.3 | 5.51 | − | 0.92 | 333.42 | 6 | 680.85 | 21.54 | 0 | 1 |
| 46 | −5.64 | − | −0.45 | 0.93 | 102.66 | − | 5.5 | − | 0.92 | 333.48 | 6 | 680.97 | 21.66 | 0 | 1 |
| 47 | −5.57 | − | −0.45 | − | 89.91 | 118.35 | 5.45 | − | 0.91 | 333.62 | 6 | 681.24 | 21.94 | 0 | 1 |
| 48 | −5.68 | − | −0.45 | 0.97 | 94.6 | 126.32 | 5.51 | − | 0.92 | 333 | 7 | 681.99 | 22.68 | 0 | 1 |

Note: The full model (encounter, density, sigma and ASU) contains 10 parameters, and the encounter probability model includes the intercept and covariates of occasion-specific temperature, temperature-squared, pike size class and individual behaviour. The density model includes the population size estimate N̂ of pike (≥60 cm) and the population size for session 2 (N̂₂). Sigma is the intercept of the movement model. The ASU model contains two covariates and no intercept; they are the distance to north shoreline (DNS) and the distance to vegetation (DV). Logit scale estimates are presented for the encounter model, density estimates are in the original scale, whereas log scale estimates are presented for sigma and ASU models. (−) denotes that the variable is not included in the model.
shoreline and distance to emergent vegetation; this is the asymmetric space-use model (ASU). Furthermore, ASU models give more realistic home ranges (Figure 6) and hence a more realistic capture probability, because of the individual’s exposure to the sampled area was modelled in more detail (Royle et al., 2013). This, in turn, mitigates the negative biased estimates of population size related to symmetric home-range models (Sutherland et al., 2015). In addition, the ASU model directly estimate an animal’s habitat use (Figure 5), that is the landscape covariate

| Model | Covariate | Coefficient  | $\hat{\theta}$ | SE ($\hat{\theta}$) | $\omega_+$ |
|-------|-----------|--------------|----------------|-------------------|-----------|
| Encounter | Intercept | Intercept | -5.686 | 0.382 | 1.00 |
| Temperature | Temperature | 0.593 | 0.203 | 1.00 |
| Temperature2 | Temperature2 | -1.133 | 0.126 | 0.69 |
| Size of fish | 60–80 cm | -0.156 | 0.305 | 0.35 |
| Behaviour | Behaviour | 0.364 | 0.598 | 0.40 |
| Density | Intercept | Intercept | -1.999 | 0.246 | 1.00 |
| Session | Session2 | -0.015 | 0.097 | 0.27 |
| Sigma | Intercept | Intercept | 5.817 | 0.371 | 1.00 |
| ASU | DNS | 0.013 | 0.003 | 0.99 |
| DV | 0.266 | 0.081 | 1.00 |

**TABLE 2** The model averaged parameter estimate $\hat{\theta}$, the model averaged standard error SE ($\hat{\theta}$) and relative variable importance ($\omega_+$) of the models (encounter, density, sigma, and ASU) based on the competing models introduced in Table 1.

**FIGURE 4** The effect of temperature on encounter probability as predicted by the best model (a), and observed captures plotted against temperature (b). The solid line in (a) is the responses predicted by the best model (model 1 in Table 1); the dashed lines are the respective 95% CI. Points in (a) are the observed $x$-values with random noise to prevent overlap, and points in (b) are the observed $x$- and $y$-values. The line in (b) is a second-degree polynomial to aid visualisation.

**FIGURE 5** Relative probability of pike space use for each pixels on the landscape relative to a pixel of zero distance from north shoreline (DNS) and zero distance from vegetation (DV), assuming a fixed distance to the individual’s home-range centre. The maximum possible probability of landscape use equals to $e^0 = 1$, that is $e^{0.013 \times DNS + 0.266 \times DV}$. Coordinates are in SWEREF 99 TM, where 1 unit corresponds to 1 m.
applied to the ASU model is a movement resistance surface and hence
describes what types of habitat that respectively facilitate and impede
animal movements (Royle et al., 2018). As such, the landscape covari-
ate is an estimate of connectivity and may aid in decision making for
fisheries management, such as restoration by connecting fragmented
habitats or in preventing the exploitation of habitats important to the
species.

This study had a very general aim and investigated the possibil-
ity of using data from recreational angling to estimate population
size of pike. However, SCR studies could allow for the investigation
of complex and specific effects on pike density, encounter and/or
movements. For instance, specific questions that are not of direct
ecological nature such as angler behaviour, and lure type and size
can be addressed, factors that are known to affect encounter rate of
pike (Arlinghaus et al., 2017, 2008). More so, data from recreational
anglers can be used with stratified sampling to monitor and compare
population size over time. The 10 pike caught during one fishing oc-
cassion comprise 11.1% of the lake’s total population of large pike. If
an angler can catch and potentially harvest, depending on regula-
tions, such a large proportion of a pike population during 1 day, how
has fishing modified the populations during the decades? It is virtu-
ally unknown how the pike populations of today compare with the
populations during pristine conditions. Furthermore, SCR models
can directly compare both the encounter probability and population
size between areas (Sutherland et al., 2018). Thereby, it is possible
to separate the encounter probability from population size, that is
areas where encounters are more frequent might not have higher
densities of fish, but instead individuals that are more easily caught.
Moreover, future studies could estimate sex-specific responses, for
encounter probability, density and animal movements (Sutherland,
Royle & Linden, 2019). As a word of caution, if the study focuses
on large pike, the number of males will inevitably be lower than the
number of females, because of sexual dimorphism, and perhaps the
sample size of males will be too low to estimate parameters accu-
rately. Therefore, preferably also smaller-sized pike than in the pres-
ent study should be included in future studies aiming for sex-specific
responses, assuming that recreational anglers feel confident that
they can sex fish visually and accurately, for instance as described
by Casselman (1974). All in all, fishing journal data by anglers may
contribute to estimation of population size, as well as estimating the
 catches relative to the population size and many other parameters of
interest, given catch and release fishing.

Any capture–recapture study is prone to loss of information in
various ways. For instance, the death of a captured individual during
the course of the study will lead to an overestimation of the popula-
tion size (Royle et al., 2013). The accuracy can be increased by strati-
fied sampling (the present study) or by reducing the sampling period,
as it is likely that demographic changes increase with the length of
the sampling period (Fuller et al., 2016). Mistaken identity can also
lead to an overestimation of population size, as one individual be-
comes two, which will lower the encounter probability and inflate
the population size. The unstructured spatial sampling procedure,
used in the present study, is a common method in SCR studies when
scat hunting dogs sniff for scat along paths that are not predeter-
mined. In such sampling designs, the sampled area is divided into
cell grids where the centroid of each cell acts as an effective trap.
Individuals captured within each cell is attributed the coordinates
of the centroid instead of its actual location of capture. This entails
individuals move through the same spawning grounds year after first captured. Since pike show spawning site fidelity, that is many 80% of recaptures were made in the same area where the pike were 10 km from the point of release. During the spawning season, 60%– Karås and Lehtonen (1993) recaptured 80%–95% of their pike within a different spatial sampling procedure. In the Baltic Sea, for instance, areas where pike could move over larger distances, it would require from migrating in and out. If a similar study were to take place in The present study took place in a small lake, where fish are hindered and ecosystem levels (Sutherland et al., 2018; Williams et al., 2002). A decline in population size of pike has been noticed in many parts of the Baltic Sea (Andersson et al., 2000; Lehtonen et al., 2009; Ljunggren et al., 2010; Nilsson et al., 2004), but causal drivers and potential remedies remain not fully understood, and any real estimate of population size in these areas remains absent. Therefore, realistic population size estimates are needed as they are fundamental for successful conservation and management, at both species and ecosystem levels (Sutherland et al., 2018; Williams et al., 2002). The present study took place in a small lake, where fish are hindered from migrating in and out. If a similar study were to take place in areas where pike could move over larger distances, it would require a different spatial sampling procedure. In the Baltic Sea, for instance, Karås and Lehtonen (1993) recaptured 80%–95% of their pike within 10 km from the point of release. During the spawning season, 60%–80% of recaptures were made in the same area where the pike were first captured. Since pike show spawning site fidelity, that is many individuals move through the same spawning grounds year after year (Engstedt, Engkvist & Larsson, 2014; Karås & Lehtonen, 1993; Miller, Kallemeyn & Senanan, 2001), the spawning sites could offer an ideal starting point for an SCR modelling study in the Baltic Sea. As the pike home-range size is probably at its smallest close to the spawning time, the trap spacing and sampling design of SCR studies on pike need to account for the time frame of the study. The trap array should be expanded until it contains some individual's home range. Then a meaningful spatial scale parameter can be estimated and used as a state space buffer for pike movements extending from the trap array.

This study showed that recreational anglers can provide valuable data for pike population size estimates. The collaboration between anglers, researchers and managers offers a possibility to further develop conservation and management of pike populations. Anglers may also help by providing data from small and remote lakes that are not included in any management programmes on a national level (Birk et al., 2012). The method presented in this study can be applied in areas with any fish populations of interest when a catch and release fishing management procedure is adapted. Therefore, further collaboration between anglers and researchers should be encouraged to have a general view of the current status of pike populations and to further improve their conservation and management policies.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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