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ARTICLE

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Estimating recreational trap-fishing effort for crayfish from zig-zag line transects, drone surveys and enforcement surveys

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Abstract

Estimates of recreational fishing effort and catch are needed to inform fisheries management, but such estimates can be challenging to obtain. We combined a zig-zag line transect survey of buoys, a fisheries enforcement survey and a drone survey to estimate recreational effort in the open-access trap fishery for signal crayfish (*Pacifastacus leniusculus*) in the sixth largest lake in Europe, Lake Vättern, Sweden. Using supporting variables such as size of nearby ports and bathymetry, our model-assisted estimate of total effort was 6400 (±4300 CI) buoys during the three-weekend season. Using the frequency of buoys to traps as a constant, the total number of crayfish traps was estimated to be 25,500 (±17,000 CI). The sampling design and methods presented are useful for ecologists and resource managers to design future multi-source surveys of recreational trap fishing effort.

KEYWORDS

design-based estimation, inland fisheries, model-based estimation, recreational fisheries, *Pacifastacus leniusculus*, signal crayfish, survey sampling

1 | INTRODUCTION

Successful management of commercial and recreational fisheries depends on accurate information of total catch and effort (Arlinghaus et al., 2019; Cooke & Cowx, 2004; Hyder et al., 2020; Radford et al., 2018; Zarauz et al., 2015). However, recreational fishing effort and catch can be difficult to estimate, so survey methods need to be developed and combined (van der Hammen et al., 2016). The use of modern technology is rapidly expanding the survey toolbox with various forms of mobile applications and internet-based approaches that can provide detailed citizen science data efficiently at a relatively low cost (Johnston et al., 2022; Lennox et al., 2022; Venturelli et al., 2016). Still, use of non- (or semi-) probabilistic approaches should be used with care to avoid or minimize bias (Brick et al., 2022), which can occur if catch, effort, or other characteristics differ between users and non-users (Gundelund et al., 2020; Lewin et al., 2021). If the purpose of a survey is to estimate total fishing effort, a range of probabilistic survey methods are available (Pollock, 1994) and combining traditional instantaneous counts with modern technology, such as aerial drones, are promising (Dainys et al., 2022; Provost et al., 2020).

When performing probabilistic surveys, sampling can be designed in a variety of ways. A standard method for surveying birds and other terrestrial wildlife is the use of strip transects, which differ from line transects by having a fixed width wherein observations are less prone to distance or movement bias (Burnham & Anderson, 1984; Glennie et al., 2015). Parallel strip transects have also been proposed as a method to estimate recreational fisheries effort by counting buoys in a trap fishery for lobster (Kleiven et al., 2011). A calibration study can ascertain suitable transect width based on the probability of detecting a buoy declining at a specified distance from the transect (Kleiven et al., 2011). As the aim is to survey an area, replicate strip transects are needed and replicates need to be spaced a certain distance from each other (at least twice the observation width). Thus, parallel strip transects can be inefficient because they require transportation between "active" strips, i.e. the transect parts that are actually surveyed. In contrast, a zig-zag pattern, where each predefined turn directly becomes a new "active" strip, provides a more efficient use of valuable sampling time, while maintaining statistical integrity (Harbitz, 2019; Strindberg & Buckland, 2004).

The signal crayfish (*Pacifastacus leniusculus*), originating from North America, was introduced to Europe in the 1960s and is now an invasive alien species of concern (EU Regulation 1143/2014). It was introduced after native populations of Noble crayfish (*Astacus astacus*) collapsed in response to the crayfish plague (*Aphanomyces astaci*) in the 1930s (Henttonen & Huner, 1999). Today, management of the signal crayfish needs to find cross-sectoral solutions that consider both international agreements on invasive species (EU Regulation 1143/2014) and resource use in commercial and recreational fisheries (Kourantidou et al., 2022). To facilitate such solutions, cross-sectoral fisheries management is today often framed within an ecosystem-based approach, which has many similarities with fisheries co-management (Cucuzza et al., 2021). To advice management processes, scientific estimates of difficult-to-obtain recreational effort and catches can provide credibility and legitimacy for discussions within the "interaction triangle" of managers, stakeholders and scientists (Röckmann et al., 2015).

Our objective was to determine if recreational fishing effort could be estimated efficiently in an open-access trap fishery that spanned only three weekends over a large geographical area. Effort was primarily measured as the total number of buoys marking crayfish traps. The number of buoys was counted in a sample of zig-zag line transects that were selected using a probability-based two-stage sampling design. Effort was also measured as the total number of crayfish traps, which was estimated from supplementary data on the number of traps per buoy collected in a fisheries enforcement survey. A limited drone survey was used to investigate fine-scale temporal dynamics of the fishery and to validate assumptions of the buoy survey. Effort for the crustacean recreational fishery was then estimated with support from regression analysis.

2 | METHODS

2.1 | Study area

Lake Vättern is the second largest lake in Sweden and the sixth largest lake in Europe (1912 km^2). Signal crayfish, which was introduced in 1969, today sustains a profitable commercial fishery that increased in the mid-1990s. Commercial landings increased from less than one ton in 1994 to about 30 t in 2004 and between 100 and 150 t annually since 2012. During the last 10 years, signal crayfish catches has represented about 90% of the annual value of the commercial fishery in the lake (Persson et al., 2021). Recreational fishing effort and catch (both private and public waters) is largely unknown, but non-peer-reviewed literature (i.e. gray literature and unofficial statistics) suggests that ~40,000 traps in the open-access fishery harvested 16 t during five weekends in 2015 (Linderfalk et al., 2018).

Fisheries management of Lake Vättern is advised by a co-management group working towards an ecosystem-based fisheries management (Bryhn et al., 2021). To facilitate discussions, information was needed about the relative importance of four types of fisheries for crayfish: (i) a licensed commercial fishery (~20 personal licenses); (ii) tourism charter fishing under special permits (~7 companies); (iii) recreational fishing in private waters, with unknown effort, no regulations and no reporting requirements; and (iv) a seasonal open-access trap fishery in public waters (unique in Sweden, in all other waters, a permit from the fishing-rights owner is required to fish for crayfish). The open-access fishery started in 2000 and regulations were last updated for the 2020 fishing season, when the number of open weekends was reduced from five to three and a maximum catch of 60 crayfish per day per fisher was introduced. Updated regulations attempted to reduce the risk of non-native crayfish being introduced to other waters (Vätternvårdsförbundet, 2017, EU Regulation 1143/2014). The open-access fishery is restricted to "public waters," defined as water areas >300 m from land and islands over 100 m in size. The fishery starts on the fourth Friday in August and includes three consecutive weekends, from 17:00 on Friday through 17:00 on Sunday. A maximum of 6 traps and 60 crayfish (>10 cm total length) are allowed per person each day. Buoys that mark traps must be at least 15 cm (or a cylinder 20 cm in length and 6 cm in diameter), colored red, orange, yellow, or white and marked with an F (for public waters).

The study area consisted of public waters (>300 m from land) of Lake Vättern shallower than 20 m. The depth limitation was based on catches in monitoring data, which showed that crayfish had an affinity for shallow areas, likely related to the thermocline during the fishing season (Spjut, 2020).

For the boat survey, the study area was divided into 42 *subareas* (SAs), with an average size of 11 km^2. The size of areas was chosen with regard to the expected speed, time and distance needed for field sampling. The SAs were divided into four strata that were internally homogenous in fishing effort. The SAs were stratified by geographic position (north or south), based on monitoring data showing higher crayfish density in the northern part with expected higher recreational fishing effort (supported by commercial catches). A second stratification by high or low accessibility was created by a geographic filter function that summed the number of berths in marinas within 15 km of each SA. High and low accessibility was defined relative to the median value (Figure 1).

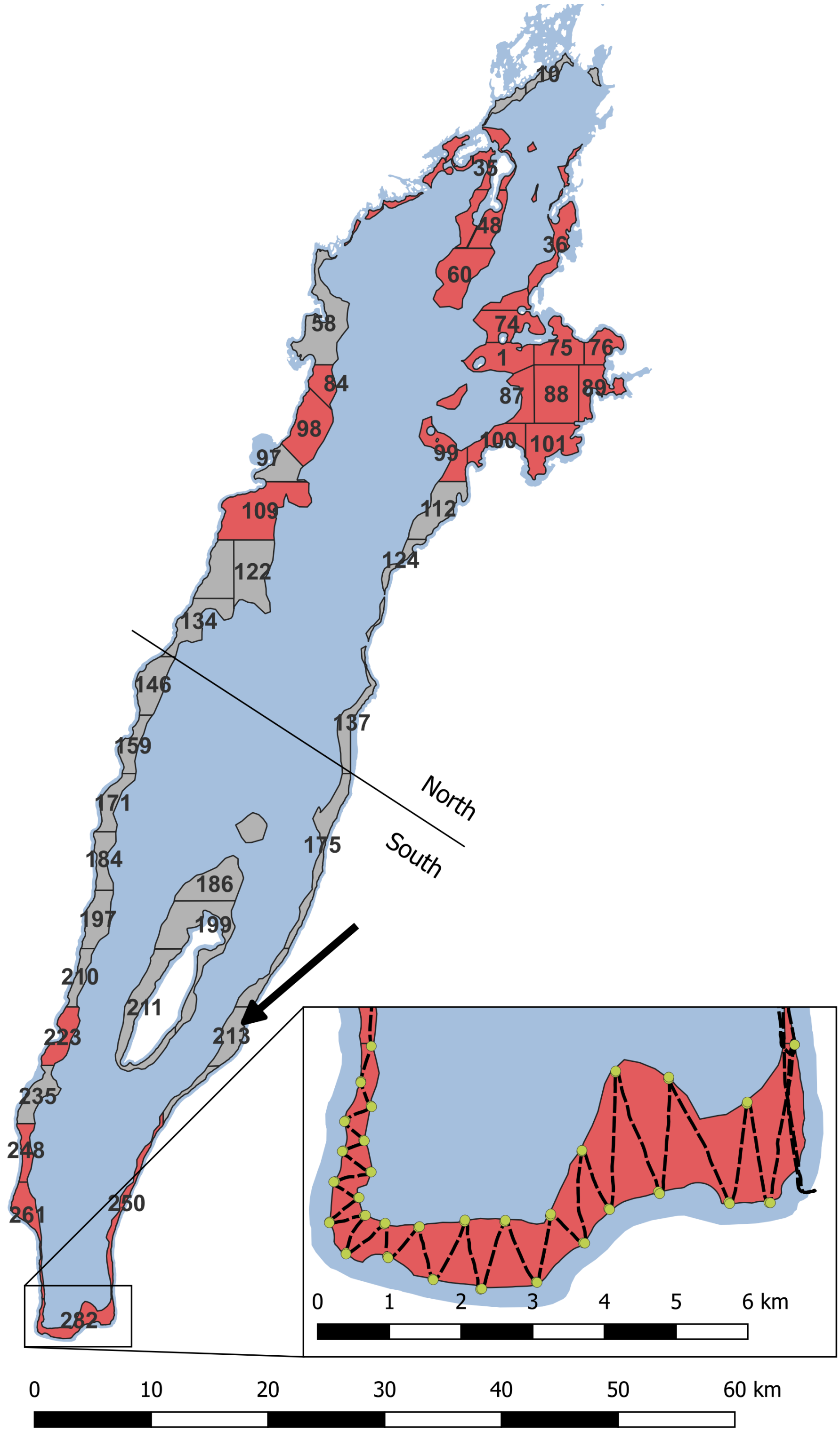

FIGURE 1 Study area in Lake Vättern, Sweden where trap effort for signal crayfish was estimated in 2021. Numbers indicate individual subareas ($N=42$) and color the strata accessibility (red = high number of berths and gray = low). North/south indicate geographic strata. The arrow shows the location of the drone survey. The magnification in the lower panel shows the zig-zag pattern of a completed transect track from the boat survey (dashed line) with GPS waypoints at the start and stop of each zig-zag segment (the track started at the harbor in the lower right corner). Subareas included in the boat survey were 10, 75, 84, 97, 98, 175, 184, 250, 261 and 282.

2.2 | Data collection

Three sets of data were collected in the field, including (i) a boat-based survey in zig-zag transects of the number of buoys, (ii) a fisheries enforcement survey of the number of traps per buoy and (iii) a drone survey of the temporal dynamics of buoys.

2.2.1 | Boat survey

The purpose of the boat survey was to count the number of buoys, in predefined transects according to the sampling design. The boat survey was on Saturdays of the three weekend-long fishing season of 2021 (August 28, September 4 and September 11). Each Saturday included two work shifts, one in the morning (06:00–10:00 hours) and one in the evening (16:00–20:00 hours). Start and end times were selected based on sunrise and sunset and anticipated behavior of recreational fishers. The morning shift measured fishing effort on Friday–Saturday and the evening shift measured effort on Saturday–Sunday. During each shift, two boat teams surveyed different areas for a total of 12 work shifts.

Each team consisted of two observers, one observing the port side and another the starboard side of the transect line that was entered in the digital navigation system. The survey focused on buoys within 50 m of the boat (100 m total width), because the proportion of buoys detected dropped beyond 50 m (Kleiven et al., 2011). Laser distance measuring tools were used to determine if the buoy was within 50 m perpendicular distance of the boat. The number of buoys inside and outside was noted for each segment of the zig-zag transect and observers were instructed to avoid potential double counting when making the zig-zag-turn. The GPS-position and depth were recorded at the start and end of each zig-zag segment (Figure 1).

The estimation method assumed that all buoys were observed without error, so observers were instructed to prioritize a suitable travel speed to ensure high-quality measurements, rather than hurrying to finish all zig-zag transects within a work shift. This assumption was verified using paired *t*-tests of counts on port and starboard sides, with an expectation that the two were equal in the absence of observation bias. Systematic differences could occur if more buoys were on the shore side than the lakeside of transects, but the position of transects within SAs and the start and direction of transects were random, so we assumed *t*-tests adequately tested for observer bias.

The first weekend was very windy during Friday and Saturday, with average wind speeds above 9 m/s (Figure S3), so the drone survey was canceled on the first Saturday, along with three of four shifts for the boat survey. To compensate, one of the SAs was surveyed on the third Saturday, rendering 10 SAs instead of the planned 12 (Figure 1). The total sample of 12 SAs was initially randomized with four SAs per weekend. The first weekend's bad weather meant that the original design could not be completed. Adjustments of weekend estimates were reported based on completed work shifts. We still assumed the estimate based on the realized allocation over weekends was random.

2.2.2 | Fisheries enforcement survey

According to regulations, up to six traps were allowed per person. The 1–6 traps could be tied together on a line and marked with a buoy, on one or both ends of the line. The fisheries enforcement survey was intended to obtain information on the number of buoys per line and the number of traps per line, to provide a buoy-to-trap frequency distribution. Only fisheries enforcement officers were allowed to check fishing gear. Because officers already monitored compliance during the open-access season of 2021, we provided protocols and requested an ad hoc survey of buoy-to-trap frequency, over the entire lake and throughout the open-access fishing season (see Figure S4 and Table S1 for exact dates and locations).

2.2.3 | Drone survey

To assess fine-scale temporal dynamics of the fishery, six stations (defined as positions for the drone) were surveyed from dusk till dawn in an area outside the town of Gränna on the eastern part of the lake (Figure 1, positions in Data S1). The stations were surveyed the same three weekends of the 2021 fishing season as the boat survey (Figure S1). When fishing crayfish, fishers usually set the traps during the afternoon or evening and collect again the following morning. We had no reason to believe that people fishing in that area behaved differently than in other parts of the lake, so we assumed that temporal dynamics of the fishery in the area sampled represented the entire lake.

The drone flew and photographed according to a pre-determined route from south to north, to reduce sun glare. Flight times were at 06:00, 07:30, 10:00, 13:00, 16:00, 18:00 and 20:00 on Saturdays and until 16:00 on Sundays (the fishery closed at 17:00 each Sunday). Altitude was 100 m and the surface that was photographed was about 100 × 100 m. At every station, two vertical photos were captured 1 s apart, which allowed the water surface to change between photos and increase the chances of detecting buoys among waves. To ensure high-quality counts of buoys, two people (readers) independently counted buoys on photographs. The comparison between readers was based on a linear regression between each reader's average number of buoys counted per date and hour.

Generalized linear mixed models using a Poisson distribution were fitted with the lme4 package in R to quantify how the number of buoys varied with weekend, day and time of day (Bates et al., 2015; R Core Team, 2022). Model residuals were evaluated with the package DHARMa (Hartig & Lohse, 2022) and pairwise comparisons were calculated with emmeans (Lenth et al., 2022). The number of buoys per weekend was modeled using time (h) as a random effect. Based on the result, weekend and time were used as random effects to examine if there was a difference between days (Saturdays and Sundays). Lastly, date was used as a random effect when modeling the effect of time.

2.3 | Estimation

2.3.1 | Population and main parameter

The target population of the survey was defined in spatial and temporal dimensions. Spatially, the population included all relevant parts of Lake Vättern, and temporally, the population included all three weekends when fishing was allowed in 2021. For this two-dimensional target population, the total number of buoys (the main parameter) was estimated for all three weekends, in addition to the total number of crayfish traps.

For the spatial dimension of the target population, the water surface of the lake was denoted U, and the number of buoys was an attribute of U. The total number of buoys on the whole surface at a given point in time was denoted t_y. Formally, this parameter was described by the integral,

$$t_y = \int\int_U y(x,z)\mathrm{d}z\mathrm{d}x,$$

where $y(x,z)$ was the number of buoys at point $(x,z) \in U$. Similarly, the number of crayfish traps was an attribute of U. The total number of traps used on the whole surface at a given point in time, denoted t_c, was described by,

$$t_c = \int\int_U c(x,z)\mathrm{d}z\mathrm{d}x,$$

where $c(x,z)$ was the number of crayfish traps at point $(x,z) \in U$.

The temporal dimension of the target population included three weekends with open-access fisheries. The total number of buoys on the lake at all times in the study period was denoted t_y^T. Correspondingly, the total number of crayfish traps on the lake at all times in the study period was denoted t_c^T.

2.3.2 | Sampling design

From the spatial population U, a probability sample of zig-zag transects was selected using a two-stage sampling design. In preparation for sampling in stage one, the spatial target population U was divided into $N_I = 42$ smaller geographical areas (SAs), $U_1, \ldots, U_i, \ldots U_{N_I}$. The set of all N_I SAs was denoted U_I of size N_I. The SAs constituted primary sampling units (PSUs). For simplicity, the ith SA was represented by its label i. The total t_y were expressed as a sum over all SAs,

$$t_y = \sum_{U_I} t_{yi}, \quad (1)$$

where t_{yi} was the number of buoys in SA i, $i = 1, \ldots, N_I$.

Sampling stage one

From U_I, a stratified sample s_I of SAs of size $n_I = 12$ was selected. Within each of four strata (Figure 1), SAs were selected using πps sampling by Sampford's method (Sampford, 1967). In πps sampling, inclusion probabilities of sampling units were proportional to area, sampling was without replacement, and the sample size was fixed. To improve precision of estimates, πps sampling was used. Within the total sample s_I, strata with high accessibility and on the north side of the lake were allocated larger sample sizes.

Sampling stage two

From each SA $i \in s_I$, a systematic sample s_i of line transects, labeled $k = 1, \ldots, n_i$, was selected. Zig-zag line transects constituted secondary sampling units (SSUs). Under the assumption that buoys were observed without error, the sample of zig-zag legs within a SA corresponded to a sample of rectangular plots of twice the observation width. Successive legs of the zig-zag were assumed to be independent, although the continuous zig-zag line within each SA was not strictly probabilistic. Per SA, the total transect length was 37 km, the distance traveled by a boat driving at five knots/hour for 4 h and coverage rates constant (total transect length divided by SA area). Transects were laid out on a map, with necessary adjustments for lake geography.

2.3.3 | Estimation of total number of buoys for a single point in time

To estimate t_y, a regression estimator was used for a two-stage sampling design with auxiliary information available on the PSU level. The $\mathbf{u}_i$ denoted a vector of auxiliary variables for SA i; $i = 1, \ldots, N_I$. In the regression model, for $i = 1, \ldots, N_I$, the expected value of t_{yi} was $\mathbf{u}_i'\boldsymbol{\beta}_I$ and the variance of t_{yi} was σ_{Ii}^2. The regression estimator of t_y (Särndal et al., 1992, result 8.4.1) was,

$$\hat{t}_{yr} = \sum_{s_I} g_{is_I} \frac{\hat{t}_{yi}}{\pi_{Ii}}, \quad (2)$$

where $\hat{t}_{yi}$ was a design-unbiased estimator of t_{yi} with respect to sampling stage two, π_{Ii} was the first-order sample inclusion probability for SA i; $i \in s_I$ and g_{is_I} was the "g weight" for SA i:

$$g_{is_I} = 1 + \left(\sum_{U_I} \mathbf{u}_i - \sum_{s_I} \frac{\mathbf{u}_i}{\pi_{Ii}} \right)' \left(\sum_{s_I} \frac{\mathbf{u}_i \mathbf{u}_i'}{\sigma_{Ii}^2 \pi_{Ii}} \right)^{-1} \frac{\mathbf{u}_i}{\sigma_{Ii}^2}$$

In Equation (2), the total weight assigned to $\hat{t}_{yi}$ was the product of the sampling weight $1/\pi_{Ii}$ (from the sampling design in stage one) and the g weight (from the regression model). This product was the calibrated weight and was calculated for each SA. The g weights were calculated so calibrated weights were (i) as close as possible to original sampling weights, to (ii) produce perfect estimates when applied to each auxiliary (regression) variable. If auxiliary variables were strongly correlated to the study variable, calibrated weights should produce good estimates (Deville & Särndal, 1992).

The regression estimator in (2) was approximately design-unbiased for t_y. The regression estimator was model-assisted, but not model-dependent, because its basic statistical properties did not depend on whether the model held. We chose a regression estimator rather than a design-unbiased (Horvitz–Thompson) estimator of t_y to increase precision. For unbiased estimation (Data S1: 4.1.), an unbiased estimator of the approximate variance of $\hat{t}_{yr}$ was,

$$\hat{V}\left(\hat{t}_{yr}\right) = \sum \sum_{s_I} \left(\frac{\pi_{Iij} - \pi_{Ii}\pi_{Ij}}{\pi_{Iij}} \right) \frac{g_{is_I} d_i}{\pi_{Ii}} \frac{g_{js_I} d_j}{\pi_{Ij}} + \sum_{s_I} \frac{g_{is_I}^2 \hat{V}_i}{\pi_{Ii}}, \quad (3)$$

where $d_i = \hat{t}_{yi} - \hat{t}_{yip}$, $\hat{t}_{yip}$ was a predicted value for t_{yi} from a regression model, π_{Iij} was the second-order inclusion probability of SA $i \& j \in s_I$, and $\hat{V}_i$ was an unbiased estimator of the variance V_i of $\hat{t}_{yi}$; $i \in s_I$.

For the estimators $\hat{t}_{yi}$ of t_{yi} and $\hat{V}_i$ of V_i in Equations (2) and (3), the n_i selected transects in SA i were selected uniformly and independently across the entire SA area (thus ignoring the zig-zag pattern). D_i denoted the density (i.e. number of buoys per unit area) of SA i; $i \in s_I$. An unbiased estimator of t_{yi} with respect to stage two was,

$$\hat{t}_{yi} = \frac{A_i}{n_i} \sum_{s_i} \hat{D}_k,$$

where A_i was the area of SA i, $\hat{D}_k = y_k / (L_k 2w)$ was an approximately unbiased estimator of D_i based on transect k (zig-zag transects were not exact rectangles), y_k was the number of observed buoys in transect k, and L_k was the length of transect k; $k \in s_i, i \in s_I$. An approximately unbiased estimator of V_i was,

$$\hat{V}_i = \frac{A_i^2}{n_i(n_i - 1)} \sum_{s_i} \left(\hat{D}_k - \hat{D}_i\right)^2,$$

where $\hat{D}_i = \sum_{s_i} \hat{D}_k / n_i$.

The g weights and predicted values in Equations (2) and (3) were calculated from a regression model with three auxiliary variables on PSU level: area, total biomass and the number of berths within 15 km. For calculation of g weights, function “calib” in the R package Sampling was used (Tillé & Matei, 2021).

2.3.4 | Estimation of total number of buoys for the study period

In the boat survey, the original randomization of SA per weekend was changed due to bad weather on the first weekend, so the actual distribution of observed SAs over weekends was considered in the estimator. To estimate the total number of buoys during the entire study period, t_y^T, the subset of s_I observed during weekend q was denoted as s_{Iq}; $q = 1, 2, 3$. The probability of including SA $i \in s_I$ in s_{Iq} was denoted by p_{Iq}. Total observation effort was allocated over the three weekends as follows: $p_{I1} = 1/10$ of selected SAs were observed during weekend 1, $p_{I2} = 4/10$ during weekend 2 and $p_{I3} = 5/10$ during weekend 3. Therefore, estimation weights were $w_i = 1/(p_{Iq}\pi_{Ii}) = T_q/\pi_{Ii}$, where $T_q = 1/p_{Iq}$, for $i \in s_{Iq}$; $q = 1, 2, 3$. Modification of Equation (2) yielded a regression estimator of t_y^T,

$$\hat{t}_{yr}^T = \sum_{s_I} T_i g_{is_I} \frac{\hat{t}_{yi}}{\pi_{Ii}}. \quad (4)$$

The T_is were treated as constants, so use of Equation (3) yielded an estimator of the variance of $\hat{t}_{yr}^T$,

$$\hat{V}\left(\hat{t}_{yr}^T\right) = \sum_{S_I} \sum_{S_I} \left(\frac{\pi_{Iij} - \pi_{Ii}\pi_{Ij}}{\pi_{Iij}}\right) \frac{T_i g_{is_I} d_i}{\pi_{Ii}} \frac{T_j g_{js_I} d_j}{\pi_{Ij}} + \sum_{S_I} \frac{T_i^2 g_{is_I}^2 \hat{V}_i}{\pi_{Ii}}. \quad (5)$$

TABLE 1 The number of buoys (B) and traps (C) fished for signal crayfish in Lake Vättern, Sweden, in 2021.

	C (No. of crayfish traps)				
B (No. of buoys)	**1**	**2**	**3**	**6**	**$p_B(b)$**
1	0.085	0.019	0.005	0.509	0.618
2	0.000	0.000	0.000	0.382	0.382
$p_C(c)$	0.085	0.019	0.005	0.892	1

An unbiased estimator of t_y^T is shown in Data S1: 4.2. Aside from estimating the variance, we also calculated a 95% confidence interval for t_y^T, based on the t-distribution.

2.3.5 | Estimation of the total number of crayfish traps for the study period

The total number of crayfish traps was estimated from the observed number of buoys along zig-zag transects and the observed number of crayfish traps per buoy in the enforcement survey. In a survey context, these observations were generated from a superpopulation for which the population was unknown and observations (in the sample) depended on the chosen superpopulation model (Särndal et al., 1992, section 14.5). The superpopulation model was therefore defined as the joint mass function of the number of buoys used on a line (B) and the number of crayfish traps on the line (C) (Table 1). The model assumed that SAs did not differ with respect to B and C and that B and C were distributed the same for all fishers throughout the lake.

The total number of crayfish traps for the study period was defined as $t_c^T = R t_y^T$, where $R = C/B$. A model-based estimator of t_c^T was

$$\hat{t}_{cr}^T = \frac{\alpha}{\beta} \hat{t}_{yr}^T, \quad (6)$$

where α and β were expected values of C and B, with respect to the model. When estimating the variance of $\hat{t}_{cr}^T$, R was assumed to be constant. The resulting variance estimator was,

$$\hat{V}\left(\hat{t}_{cr}^T\right) = \left(\frac{\alpha}{\beta}\right)^2 \hat{V}\left(\hat{t}_{yr}^T\right), \quad (7)$$

By treating R as a constant, the variance estimator was simple but underestimated the total variance of $\hat{t}_{cr}^T$. Equations for the total variance can be found in Data S1: 4.3.

3 | RESULTS

The total number of buoys during the three-weekend-long fishing season was 6413 buoys (95% confidence interval = 4302 buoys). The total number of buoys observed in all 10 SAs ranged 2–56 per SA and totaled 203 buoys. Average density of buoys was 8.5 buoys/km^2 and SA (SD = 7.2 buoys/km^2, range = 0.8–21 buoys/km^2). Average transect depth was 20.2 m (SD = 9.5 m, median = 17.6 m, range = 3.4–58 m) from start and stop points of each zig-zag transect. Fishing was concentrated in shallower areas (Figure 2b) and no buoys were observed on transects with an average depth below 32 m.

Buoy counts within 50 m transects were unbiased because the number of buoys counted inside the transect did not differ significantly between port and starboard sides (Paired-t = 0.309, df = 205, p = 0.76, mean port = 0.50 buoys, mean starboard = 0.48 buoys). In contrast, buoys counted outside the transect (>50 m on each side) were biased because the number of buoys counted differed significantly between port and starboard sides (Paired-t = −2.76, df = 205, p = 0.006, mean port = 1.2 buoys, mean starboard = 0.72 buoys).

The 210 buoys controlled by fisheries enforcement officers were evenly spread over the fishing season and in both north and south parts of the lake (Figure S4, Table S1). Controlled buoys were in shallower water than in the boat survey, at an average depth of 9.9 m

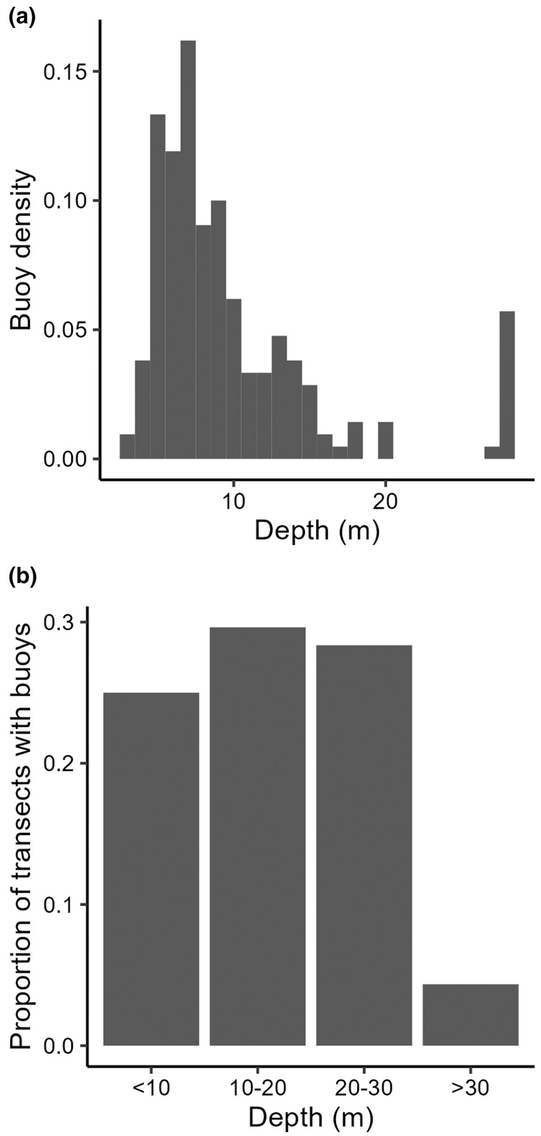

FIGURE 2 Fishing depths of traps fished for signal crayfish based on a fisheries enforcement survey (a) and average depth of transects with buoys from a buoy survey (b) ($N_{<10}$ = 8, $N_{10\text{-}20}$ = 108, $N_{20\text{-}30}$ = 67 and $N_{>30}$ = 23) in Lake Vättern, Sweden in 2021.

(SD = 5.7 m, median = 8.0 m, range = 2.9–27.7 m, Figure 2a). The number of traps per buoy was most commonly 6 traps (89.2%), followed by 1 trap (8.5%). Only lines with 6 traps had two buoys (Table 1). Based on the buoy-to-trap frequency as a fixed variable, and using Equations (6) and (7) and a t-distribution, the number of traps was 25,455 (95% confidence interval = 17,080). Based on the variance of the buoy-to-trap frequency, the 95% confidence interval was 29,005, which overlapped zero (see Data S4).

3.1 | Drone survey

Buoy counts were highly consistent between readers (intercept = 0.02 ± 0.05, slope = 1.05 ± 0.05 SE, $F_{(1,26)}$ = 426.4, p < 0.001, R^2 = 0.94, Figure S2). The number of buoys did not differ on the first and second weekends (z ratio = −0.977, p = 0.329), but was lower on the third weekend than on the first weekend (z ratio = 5.755, p < 0.0001) and second weekend (z ratio = 5.902, p < 0.0001, Figure 3).

The number of buoys did not differ between Saturdays (mean = 0.82, CI 0.32–2.1) and Sundays (mean = 0.73, CI 0.28–1.9, z value = 0.548, p = 0.584). The number of buoys counted differed between start and stop times for both morning and evening shifts, but not between shifts (06:00–10:00 hours, z ratio = 2.461, p = 0.014; 10:00–16:00 hours, z ratio = −0.170, p = 0.865; 16:00–20:00 hours, z ratio = −2.180, p = 0.029, Figure 4). At the start of the morning shift (0600 hours), twice as many buoys (mean = 0.93, CI 0.4–2.2) were counted than at the end of the shift (10:00 hours: mean = 0.45, CI 0.3–0.9), which indicated that buoys set out the night before were removed during the morning shift. In contrast, half as many buoys were counted at the start of the evening shift (16:00 hours: mean = 0.48, CI 0.3–0.9) than at the end of the shift (20:00 hours: mean = 1.08, CI 0.6–2.2), which indicated that fishers set gear out for the night during the evening shift (see also Figure S1).

4 | DISCUSSION

We found a decreasing effort towards the end of the fishing season (Figure 3). Similar patterns have been described for lobster fisheries in Norway (Kleiven et al., 2011) and on the west coast of USA (Parnell et al., 2007). That these surveys had varying length, three weekends (this study), 8 weeks (Kleiven et al., 2011) and 24 weeks (Parnell et al., 2007), suggests that regardless of season length, trap fishers may in general reduce effort as the season progresses. Understanding how crustacean fisheries effort and catch varies in space and time is important for management (Boenish & Chen, 2018). Detailed knowledge on seasonal fishing patterns could improve future survey designs, yielding more cost-effective and precise estimates.

Results from the drone survey highlight the need to also consider fine scale temporal dynamics. Although setting traps a given day and hauling them the next day is a common pattern in trap fisheries (Bañón et al., 2018), our hourly patterns of fishing effort suggest that sampling should be as close to sunrise or sunset

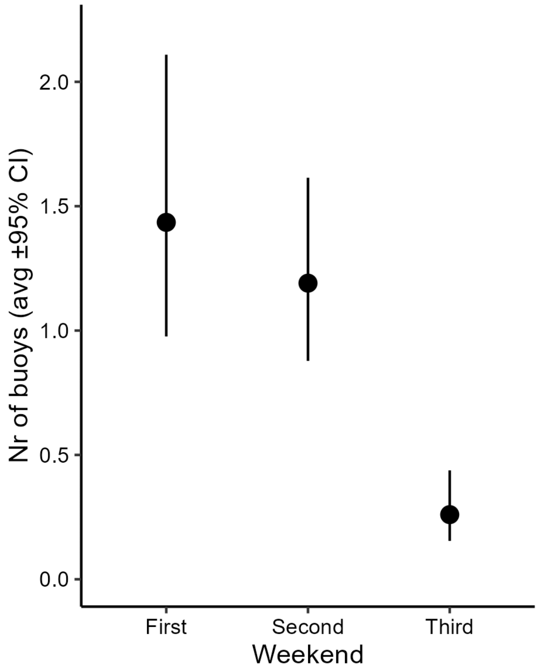

FIGURE 3 The average number of buoys (±95% CI) used for trap fishing of signal crayfish on each of three open-access weekends in Lake Vättern, Sweden, in 2021.

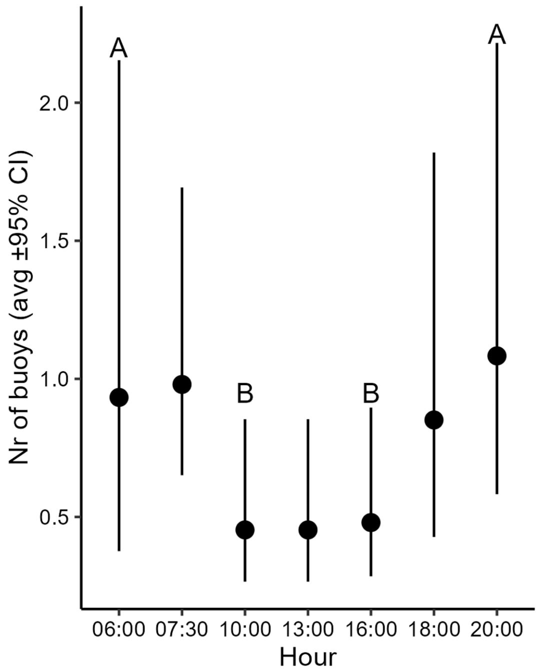

FIGURE 4 The average number of buoys (±95% CI) used for trap fishing of signal crayfish on each hour of a boat survey in Lake Vättern, Sweden, in 2021. Work shifts of the boat survey were 06:00–10:00 and 16:00–20:00. Letters indicate statistical differences within, but not between work shifts.

as possible to maximize trap counts and increase chances of encountering fishing effort. Drones, and other modern technological sources, are increasingly used to collect recreational fishing effort (Dainys et al., 2022). However, as drones are limited in flight time and require post-processing of videos or images, traditional vessel-based surveys can be more effective (Provost et al., 2020).

We found declining effort with depth in both the boat and enforcement survey. Similar patterns have been described also in lobster fisheries (Kleiven et al., 2011; Parnell et al., 2007), likely reflecting the ecology of the species and fishers' preference to minimize travel distance (Boenish & Chen, 2018; Ruokonen et al., 2012). That the enforcement survey indicated a preferred fishing depth shallower than the boat survey depended on how depth was measured. Transect depth was measured from the average depth at the start and end points of the transect, while depth along the transect where buoys were located was unknown. We recommend that future surveys of crustacean trap fisheries use reliable bathymetric grids to focus on areas of suitable depth (Kleiven et al., 2011).

Although our final estimates had relatively large margins of error, they can be useful for management, especially when uncertainty is properly acknowledged and communicated (Röckmann et al., 2012). One of the main sources of uncertainty in our study was likely the low sample sizes of the boat survey. An increased sample size for the first sampling stage could be achieved by using more than two boats to survey more SAs simultaneously. Additionally, different stratification variables and more (or other) auxiliary variables could be used in the regression model, but are system-specific and require local expert knowledge, which could potentially be improved by strong stakeholder involvement (Albuquerque et al., 2021; Olsson & Folke, 2001).

Management of recreational fisheries is often limited by lack of information (e.g. Arlinghaus et al., 2019; Cooke & Cowx, 2004), but knowledge of effort may not be enough to ensure fair and sustainable resource management when dealing with potential controversies among resource users (Linke & Bruckmeier, 2015). Hence, measurements of fishing effort, such as the number of buoys or the number of traps, should be less directly relevant than estimates of catches by other resource users (e.g. Lyle et al., 2005; Slaton et al., 2023). However, estimating catches from effort requires knowledge of catch rates, which can be variable and difficult to estimate (Kleiven et al., 2022; Pollock, 1994). Although we did not estimate catch, we propose a simple metric that can be discussed in relation to its uncertainty and potential for use in management. Based on standardized monitoring data, using gear similar to the recreational sector, 7.3 crayfish >10 cm were caught per trap night (±3.0 95% CI, Bohman, 2023). Given our estimate of ~25,500 traps, 186,000 crayfish would have been caught in the 2021 fishing season. Average weight of a crayfish >10 cm, estimated from number and weight per length group from monitoring data of another lake, Lake Mälaren (59 g/crayfish, $n = 247$), with lower fishing pressure and more large crayfish than Lake Vättern, may slightly overestimate harvest in weight. Nevertheless, if legal crayfish (>10 cm) average 59 g/crayfish in weight in Lake Vättern, total landings would have been ~11 t (2–20 t) in 2021. Effort and catch in public waters in 2015 was ~40,000 cages and 16 t during the 5-weekend fishing season (Linderfalk et al., 2018). Compared to our study, yield was quite similar, for both effort (8000 traps/

weekend in 2015 and 8500 traps/weekend in 2021) and catch (3.2 t/weekend in 2015 and 3.7 t/weekend in 2021). This comparison suggests that reduction of the fishing season from five to three weekends slightly increased average effort and catch but led to reduced total recreational fishery harvest from public waters. The ~11 t potentially landed by the recreational fishery was only 11% of the ~100 t landed by the commercial fishery. Although formal stock assessment models are lacking for the signal crayfish in Lake Vättern, the 11% relative importance of the open-access recreational catch to commercial catch was similar to some marine commercially exploited stocks where recreational catch was necessary to consider (Radford et al., 2018). A relative recreational catch of 10% has also operated as a management trigger for lobster fisheries in New Zealand (Lyle et al., 2005). Surveys that estimate recreational fishing effort and catch from public and private waters are more important when recreational catch is high in relation to commercial catch and therefore should be considered in assessments of stock status (Radford et al., 2018).

The allocation of catch proportions to different types of fisheries is ultimately a policy and management question. However, to be able to make informed decisions and balance harvest to ensure long-term sustainability, knowledge of the relative importance of different sectors is needed. Our approach to estimate recreational effort should be repeated to provide such knowledge on a continuous basis. If long-term collection is possible, the increased experience can enhance the design and decrease uncertainty of estimates. Managers that aim for sustainable resource use should however consider other potential risks than overfishing. European crayfish populations have shown a high risk of collapsing (Sandström et al., 2014). Although collapse has often been attributed to *A. astaci*, other less-known sources could be important (Edgerton et al., 2004), including introductions of predatory fish (Olsson et al., 2006) and heavy exploitation (Hein et al., 2007). Thus, uncertain estimates of effort, catch and relative importance of different types of fisheries can be useful for crayfish management and risk assessments. Perhaps especially when collected through a collaboration within "the interaction triangle" of scientists and decision-makers as it conveys a transparent and credible foundation for co-management and ecosystem-based approaches where results and their associated uncertainty can be effectively communicated with stakeholders (Bryhn et al., 2021; Röckmann et al., 2015). Taken together, we hope that our multi-source survey and estimation methods can provide guidance for others that aim to understand the dynamics and estimate effort of various recreational trap fisheries targeting crustaceans.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest for this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

No ethics approval was needed for this study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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