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Size selectivity of fyke nets for European eel *Anguilla anguilla*

D. Bevacqua*†, G. A. De Leo†, M. Gatto‡ and P. Melià‡

†*Dipartimento di Scienze Ambientali, Università degli Studi di Parma, Viale Usberti 33A, I-43100 Parma, Italy and* ‡*Dipartimento di Elettronica e Informazione, Politecnico di Milano, via Ponzio 34/5, I-20133 Milano, Italy*

Size selectivity of fyke nets for European eels *Anguilla anguilla* was investigated by reviewing the results of published experimental studies. A general size selectivity model was then derived that can be easily incorporated into demographic models to simulate population dynamics, assess and monitor abundance and length structure of eel stocks and forecast the consequences of different management options.

Key words: fisheries management; fishing gears; fishing mortality; size-selectivity curves; stock assessment and monitoring.

Stock assessment and management of European eel *Anguilla anguilla* (L.) have received increasing attention by both the scientific community and the fisheries agencies in recent years (ICES, 2007). There is growing concern on the fate of the *A. anguilla* stock, which has experienced a sharp recruitment drop in the last three decades and is presently outside safe biological limits (Anon., 2003; ICES, 2007). *Anguilla anguilla* has been recently added to Annex B of the Convention on International Trade in Endangered Species (CITES) and to the International Union for the Conservation of Nature (IUCN) Red List as a critically endangered species (Freyhof & Kottelat, 2008). The European Council has adopted a Regulation (EC, 2007) aimed at achieving the recovery of the stock through the drawing up of 'eel management plans' (EMP). EMP will be directed to assessing and monitoring the status of local populations, reducing anthropogenic mortality and enhancing spawner production. Despite the fact that anthropogenic mortality encompasses a broad range of disturbance factors (including pollution, habitat loss, human-driven transfer of parasites and viral diseases, obstacles to upstream and downstream migration), it is likely that EMP will lean mainly towards a reduction in fishing mortality. Commercial fishing can have a severe effect on the escapement of adult *A. anguilla* from continental waters (Dekker, 2000; Bevacqua *et al*., 2007), and a reduction in fishing disturbance can be attained in the short-term if sound fishery policies are devised. A variety of fishing gears is used to fish *A. anguilla* during the continental phase of their life cycle. Among these, a common passive device is the fyke net

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*Author to whom correspondence should be addressed. Tel.: +39 521 905619; fax: +39 521 905402; email: daniele.bevacqua@nemo.unipr.it

(Dekker, 1999; Tesch, 2003), which is widely used also in stock assessment. Fyke netting can be an effective alternative to electrofishing, especially where this latter method cannot be applied, *e.g.* in deeper and saline waters and at night (Naismith & Knights, 1990; Knights *et al*., 1996).

A sound evaluation of fyke net efficiency is crucial to assess fishing mortality and derive unbiased estimates of population structure from the size frequency distribution of commercial catches or scientific samples (Berg, 1990). Sound mathematical models, explicitly accounting for fishing mortality under different management scenarios, might help scientists and decision makers devising targets and means of EMP and forecasting the consequences of corrective management actions on the future viability of the *A. anguilla* stock (Bevacqua *et al*., 2007). In mathematical models used for stock assessment and demographic simulation, capture rate F is commonly expressed as the product of three factors: (1) a catchability coefficient q, which depends on the characteristics of the target species and the specific fishing gear used, (2) the fishing effort E, typically measured as the number of gears used multiplied by the fraction of time in which the gears are in use and (3) the selectivity φ, namely the fraction of fish intercepted by the gear that are effectively retained. Therefore $F = qE\varphi$. For most fishing gears, fish liability to capture depends upon body size, to which φ can be linked through a so-called size-selectivity curve, and whose determination is a key component of stock assessment (Myers & Hoenig, 1997). The selectivity φ is responsible for the typically unimodal length-frequency distribution of fish samples. In particular, the first part with positive slope results from gear selection, while the second one with negative slope is mainly determined by the size structure of the population (Berg, 1990). In this study, size selectivity of fyke nets for *A. anguilla* was investigated by reviewing the results of published experimental studies, with the aim of deriving a general size-selectivity model that can be easily used in local stock and fisheries assessments and monitoring.

Fyke nets are passive (fixed) fishing devices consisting of (1) a leader, (2) two or more chambers, connected through 'in-scales' (truncated cones conveying fish towards the next chamber but not allowing them to return to the preceding one) and surrounded by netting with decreasing mesh size and (3) a codend (Fig. 1). *Anguilla anguilla* generally perceive leader and first chamber nets as barriers, do

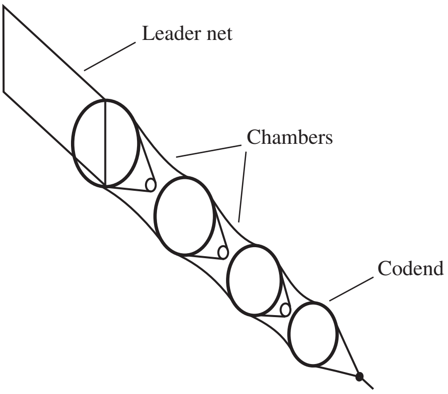

FIG. 1. Fyke net comprising a leader net, two chambers with three 'in-scales' and a codend.

not attempt to force a passage through and head for the codend where escape attempts occur (Naismith & Knights, 1990; Millar & Fryer, 1999). Therefore, size selectivity is mostly determined by the size m of the mesh openings in the codend, with larger individuals more probably retained than smaller ones. In contrast to the size selectivity of gillnets, which is typically a unimodal, bell-shaped function of fish size, that of fyke nets is generally a monotone, non-decreasing function of fish size with an upper asymptote at unity (indicating that, beyond a given body size, almost 100% of the fish are retained). This pattern can be effectively described by a sigmoid function (De Leo & Gatto, 1995):

$$\varphi(S) = \left\{1 + e^{[-\eta(S-S_{50})]}\right\}^{-1} \tag{1}$$

where S is fish size (*e.g.* body length, body mass or trunk section), S_{50} is S at which 50% of the fish are retained and η is a shape parameter defining the slope of the curve at $S = S_{50}$. $\varphi(S)$ is symmetric about S_{50} and the value of η determines the size range of the catch. Logically, size selectivity of a meshed gear should be expressed as a function of trunk section (Gatto & Rossi, 1979; De Leo & Gatto, 1995). Yet, body length (1) is considerably easier to measure than trunk section, (2) can be simply related to fish section *via* an allometric relationship and (3) is a standard biometric measure which is commonly used in fisheries management models. For this reason, net selectivity is often expressed as a species-specific function of body length. To this end, trunk section A can be derived as a function of total body length, L_T. If the shape of a fish is approximated with a cylinder, body mass M, body length L_T and trunk section A can be linked *via* the following relationship:

$$M = \rho A L_T, \tag{2}$$

where ρ is the density of the fish, assumed to be constant and equal to water density (0·001 g mm^{-3}). If a morphometric relationship $M = aL_T^b$ is available, trunk section A can eventually be written as a function of L_T:

$$A(L_T) = a\rho^{-1}L_T^{b-1}, \tag{3}$$

where a and b are the scale and shape parameters of the M and L_T relationship.

Despite the socio-economical importance of thousands of small scale *A. anguilla* fisheries scattered all over Europe (Dekker, 2003) and the increasing need of reliable tools for stock assessment and monitoring, few studies have explicitly investigated the link between net selectivity and mesh size for *A. anguilla*. Empirical studies (Gatto & Rossi, 1979; Berg, 1990; Naismith & Knights, 1990) investigated gear selectivity for specific mesh sizes by using direct (*i.e.* based on the knowledge of the population length structure and the opportunity to monitor escapement) or indirect methods (*i.e.* comparing catches obtained from an experimental gear with those of a control one). Typical outputs of the experiments were the minimum L_T ($L_{T\min}$) retained by the gear of a given mesh size m and the L_T over which all individuals are retained ($L_{\mathrm{T\,max}}$). Yet, none of these studies provided an analytical relationship linking mesh size with the parameters characterizing the size selectivity curve.

Data for this analysis were gathered from six experimental studies on net selectivity for *A. anguilla*, encompassing a range of 13 mesh sizes. Of these, only three were published in peer reviewed journals (Gatto & Rossi, 1979; Naismith & Knights, 1990; De Leo & Gatto, 1995), whilst the others were described in two PhD theses (Lee, 1979; Adam, 1997) and a technical report (Ximénès, 1986). Most studies reported gear selectivity at the codend of fyke nets. Naismith & Knights (1990), however, reported the results of laboratory tests in which recently caught wild *A. anguilla* were placed in net bags suspended in tanks and the individual sizes of fish retained or lost were recorded. To make all figures consistent, all mesh sizes were expressed as the maximum distance between two diagonally opposite knots at

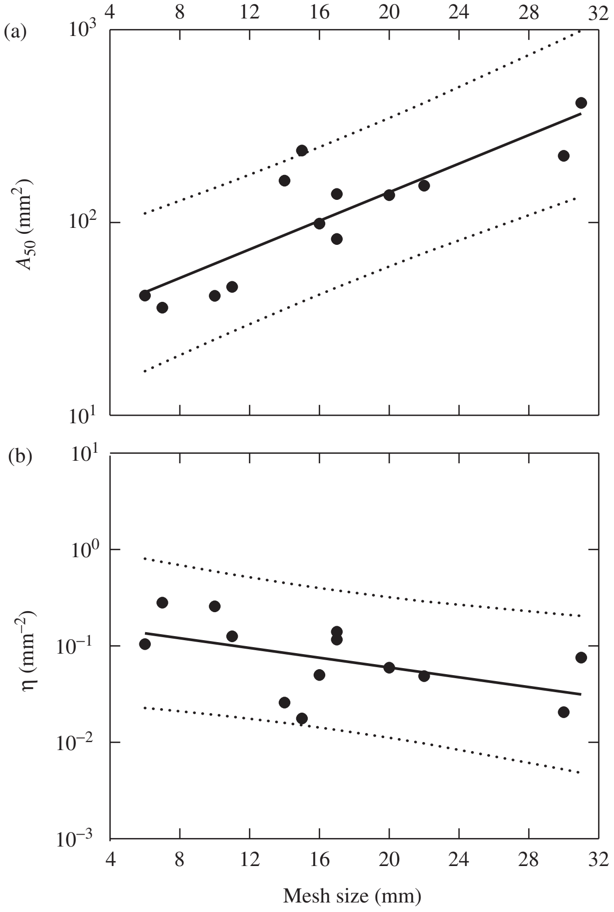

FIG. 2. Variation of size selectivity parameters for different codend mesh sizes (stretched mesh): (a) A_{50}, fish trunk section at which 50% of the fish are retained in the codend and (b) η, shape parameter defining the slope of the size selectivity curve at trunk section = A_{50} [●, parameter estimates derived from published data (Table I)]. The curves were fitted by (a) $\ln y + 3{\cdot}26 = 0{\cdot}09x$ and (b) $\ln y = -1{\cdot}65 - 0{\cdot}06x$ (…., 95% CI).

full stretch (stretched-mesh size). Where knot-to-knot mesh size was reported (*i.e.* the distance between two adjacent knots in the open mesh), stretched-mesh size was calculated by doubling the knot-to-knot mesh dimension (Ximénès, 1986).

The parameters of the size-selectivity curve (equation 1) for each population were derived as follows. First, A_{min} and A_{max}, namely the trunk sections of a fish having $L_{\mathrm{T}} = L_{\mathrm{T\,min}}$ and $L_{\mathrm{T}} = L_{\mathrm{T\,max}}$, respectively, were estimated from equation 3 using the morphometric parameters relevant to that population. Then, A_{50} (the trunk section corresponding to 50% retention) was calculated as the average of A_{min} and A_{max}. Finally, η was determined from equation 1 by supposing that a fraction α of the fish retained by the gear had a trunk section comprised between A_{min} and A_{max}. By imposing $\varphi(A_{\mathrm{min}}) = 0{\cdot}5\ (1 - \alpha)$ and $\varphi(A_{\mathrm{max}}) = 0{\cdot}5\ (1 + \alpha)$, the following is obtained:

$$\eta = \ln\left[(1+\alpha)(1-\alpha)^{-1}\right]\,(A_{\mathrm{min}} - A_{50})^{-1} = \ln\left[(1-\alpha)(1+\alpha)^{-1}\right]\,(A_{\mathrm{max}} - A_{50})^{-1} \tag{4}$$

The findings of the studies, which cover a mesh-size range between 6 and 31 mm, are summarized in Table I along with the relevant estimates of A_{50} and η. The value of η was calculated by imposing $\alpha = 0{\cdot}95$ in equation 4, which is equivalent to assuming that the probability of a fish retained by the net having body length $<L_{\mathrm{T\,min}}$ or $>L_{\mathrm{T\,max}}$ is $<5\%$. Fig. 2 displays estimated A_{50} and η against the mesh size m of the fishing gear, showing that A_{50} increased and η decreased for increasing values of m. These data were used to investigate possible relationships between the two parameters and m. A linear regression of $\ln A_{50}$ and $\ln\eta$ against m was performed to prevent the resulting models from assigning negative values to A_{50} for m near zero and to η for large m values. Significant correlations were found between $\ln A_{50}$ and m ($r^2 = 0{\cdot}73$, $P < 0{\cdot}01$) and between $\ln\eta$ and m ($r^2 = 0{\cdot}26$, $P < 0{\cdot}1$). The relevant equations are shown in Fig. 2.

Through these equations, it is easy to generalize equation 1 to encompass different values of the mesh size m:

$$\varphi(L_T, m) = \{1 + e^{[-\eta(m)\,(A(L_T) - A_{50}(m))]}\}^{-1} \tag{5}$$

where A is given by equation 3 and A_{50} and η by equations in Figs. 2(a) and 2(b), respectively. Figure 3 illustrates a possible output of the model, showing the selectivity of fyke nets with different mesh sizes for an hypothetical *A. anguilla* population. Parameters a and b (equation 3) were averaged over the six populations used in the analysis (a: geometric mean = $1{\cdot}86 \times 10^{-7}$ mm^{-b}; b: arithmetic mean = $3{\cdot}36$, as the L_{T} and M relationship is linear in ln a and b). Equation 5 can be adapted to different *A. anguilla* populations by substituting appropriate values of the morphometric parameters a and b in equation 3, and has therefore a general validity. Parameters a and b can be easily estimated through linear regression on ln-transformed L_{T} and M data.

The present model represents a generalization of experimental studies such as that of Naismith & Knights (1990), who analysed the performances of fyke nets

TABLE I. Main features of the experimental studies analysed in this work, along with relevant estimates of selectivity parameters

m (mm)	$L_{\mathrm{T\,min}}$ (mm)	$L_{\mathrm{T\,max}}$ (mm)	a (g mm^{-b})	b (–)	A_{50} (mm^2)	η (mm^{-2})	Method†	Fishing device	Reference
6	75	225	$4{\cdot}14\times 10^{-7}$	3·24	42	0·104	dir.	codend	1;2
7	150	200	$0{\cdot}44\times 10^{-7}$	3·63	36	0·281	ind.	mesh-bag	3;4
10	160	210	$0{\cdot}44\times 10^{-7}$	3·63	42	0·257	ind.	mesh-bag	3;4
11	120	230	$3{\cdot}11\times 10^{-7}$	3·28	46	0·126	dir.	codend	5
14	130	430	$5{\cdot}24\times 10^{-7}$	3·19	165	0·026	dir.	codend	6
15	150	500	$3{\cdot}11\times 10^{-7}$	3·28	236	0·018	dir.	codend	5
16	160	360	$1{\cdot}50\times 10^{-7}$	3·37	99	0·050	dir.	codend	7
17	270	330	$3{\cdot}11\times 10^{-7}$	3·28	140	0·116	dir.	codend	5
17	210	270	$0{\cdot}44\times 10^{-7}$	3·63	82	0·140	ind.	mesh-bag	3;4
20	225	345	$4{\cdot}14\times 10^{-7}$	3·24	139	0·060	dir.	codend	1;2
22	240	360	$0{\cdot}44\times 10^{-7}$	3·63	155	0·048	ind.	mesh-bag	3;4
30	200	496	$0{\cdot}94\times 10^{-7}$	3·46	222	0·021	dir.	codend	8
31	430	470	$0{\cdot}44\times 10^{-7}$	3·63	417	0·076	ind.	mesh-bag	3;4

†dir. direct method; ind. indirect method.

m, stretched-mesh size (maximum distance between two diagonally opposite knots at full stretch); $L_{\mathrm{T\,min}}$ and $L_{\mathrm{T\,max}}$, minimum and maximum total length (L_{T}) retained by the net; *a* and *b*, parameters of L_{T} and mass allometric relationship (equation 3); A_{50} and η, parameters of the selectivity curve (equations 4 and 5).

References: 1 Adam (1997); 2, Adam & Elie (1993); 3, Naismith & Knights (1990); 4, Knights (1982); 5, Ximénès (1986); 6, Lee (1979); 7, De Leo & Gatto (1995); 8, Gatto & Rossi (1979).

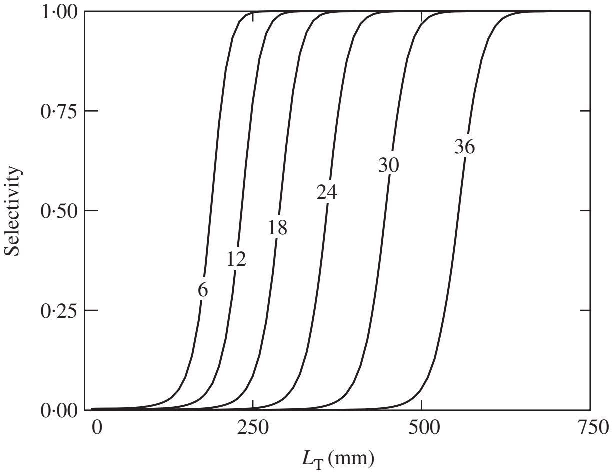

FIG. 3. Estimated total body length (L_T) selectivity curves for *Anguilla anguilla* fyke nets with different mesh sizes, showing stretched-mesh dimension (in mm) superimposed on each curve.

of different mesh size and compared them with those of other methods but did not provide an analytical expression summarizing their results. De Leo & Gatto (2001) derived a family of selectivity curves for fyke nets with different mesh sizes from the one proposed by De Leo & Gatto (1995), but did not contrast the predictions of those curves with empirical data nor proposed a procedure to adapt them to other *A. anguilla* populations. The model proposed here is not exempt from weaknesses. Environmental conditions and fish behaviour are also likely to affect fyke-net selectivity (Naismith & Knights, 1990). Fine-meshed nets in swift waters may get obstructed by debris and become ineffective or be washed away. Fish retention in the codend may be increased by crowding and stress impairing the escape of individuals that might theoretically pass through the mesh. Unfortunately, however, the influence of these factors on selectivity is poorly documented and available data do not allow incorporating these effects in a reliable way. Another weakness of the model is to assume that fyke-net selectivity is determined only by the mesh size of the codend, and to disregard the selectivity of the leader net and that of the chambers. Assuming *A. anguilla* to be shaped like an ideal cylinder is a further approximation. Trunk compressibility is not uniform and is higher in depth than in width. Although the passage through mesh apertures is typically limited by trunk size in larger fish (>250 mm L_T), the size of the head is likely to limit the passage of smaller ones (Knights, 1982). Also, the relationship linking L_T and trunk section can be affected by stomach fullness and vary during the year together with the condition factor. Despite these reservations, the general size-selectivity curve formulated in this work, based on empirical evidence from data gathered both in the laboratory and in the field, can provide useful preliminary information to evaluate the effectiveness of fyke nets used for fishing or scientific sampling of local *A. anguilla* stocks. It can be incorporated into demographic models, such as those required for the development of EMPs, which will be crucial to simulate population dynamics, assess and monitor abundance and length structure of *A. anguilla* stocks and forecast the consequences of different management options.

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