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Scientific Note

Is it time to discard the Rikhter & Efanov's natural mortality–age at maturity estimator from the stock assessment scientist's toolbox?

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Abstract. The present note highlights that age-at-50%-of-maturity instead of the original "massive maturation" (i.e., the age at which *more* than 50% of specimens are mature) descriptor has been mainly used for the Rikhter & Efanov's expression, resulting in inflated estimations of natural mortality in

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Resumen. Evaluación de la aplicación del estimador de Rikhter y Efanov para "mortalidad natural/edad de madurez" en ciencia pesquera. La edad al 50% de madurez en lugar del descriptor "maduración masiva" (edad en que más del 50% de los ejemplares están maduros) se ha utilizado para el modelo de Rikhter y Efanov, resultando en sobrestimaciones de la mortalidad natural; para evitar más malos usos, el estimador debe ser retirado.

Palabras clave: evaluación, métodos indirectos, características de historia de vida

Since the beginning of modern fishery science (e.g., Holt 1958), the natural mortality rate M or "collective forces of natural mortality" (Cushing 1968), has always been (e.g., Ralston 1987), and still is (e.g., Hoggarth *et al*. 2006), among the most difficult parameters to estimate in exploited marine stocks. In spite of innovative but often impracticable methodologies (Hewitt & Hoenig 2005), M is still difficult even to be defined (e.g., the M-F inverse relationship proposed by Munro 1982, or the M-at-age "bathtub" profile by Chen & Watanabe 1989).

The necessity of estimating M for stock assessment processes requires splitting fishing mortality (F) from total mortality (Z). That necessity compelled early managers and scientists (Taylor 1960, Le Cren & Holdgate 1962, Alagaraja 1984) to explore indirect methods of estimating M, which usually delivered no more than "guesstimates" or "qualified guesses" (Sparre & Venema 1998). At present, the available indirect methods (Vetter 1988, Hewitt & Hoenig 2005, Ragonese *et al*. 2006, Gislason *et al*. 2010, Siegfried & Sansó 2012) range from empirical regressions to invariant approaches. These methods correlate M with single (i.e., size *vs.* age-at-maturity; Beverton 1963, Rikhter & Efanov 1976, Charnov *et al*. 2012) or multiple (i.e., von Bertalanffy growth function, VBGF, parameters and seawater temperature; Pauly 1980) life history or environmental variables.

Among the regression methods, the Rikhter & Efanov's expression (hereafter R&E) published in 1976 has been often used, even in species different from finfish, such as shellfish (e.g. Pakhomov 1995, Jaramillo 2008, Conners *et al*. 2011). The R&E only requires an estimation of the age-at-maturity, a parameter considered scientifically sound (the earlier the maturity is achieved, the higher should be the mortality; Jones & Johnston 1977) and generally available in literature (ICES 2008). Unfortunately, the original paper presents some ambiguity and the aim of this contribution is to analyse the effects of such ambiguity on M estimations.

Fisheries science literature was examined to determine how the R&E expression has been interpreted and applied. The starting point was the original expression and corresponding symbols/definitions (Rikhter & Efanov 1976):

$$Y = 1.521 / x^{0.72} - 0.155$$

where Y and x represent the instantaneous natural mortality rate (M) and the age-at-massive-maturation (i.e., "the age at which the share of mature specimens exceeds 50%"), respectively, whereas the coefficients 1.521 and 0.155 have been estimated by regressing two sets of ages at maturity and M values considered "true" (herein M_{true}), as suggested in Rikhter & Efanov (1976: pages 3-5).

First of all, looking at the data reported in the first table of the original R&E paper, it is evident (and logical) that the ages-at-first-maturity (herein a_{m50}) were lower than the corresponding ages-at-massive-maturation (herein a_{MM}) in 9 out 12 instances (from 1-2 up 7 years). In such cases, using a_{m50} instead of a_{MM} in the R&E resulted in different M_{m50} and M_{MM} estimations; in particular, the mean difference (and corresponding standard deviation, sd) between the R&E estimations and M_{true} were + 0.28 (± 0.17) and - 0.02 (± 0.06) for M_{m50} and M_{MM}, respectively. Using M_{m50} results in a significant (paired t-test, t_s= 4.9 > critical t_s= 1.89; 7 degree of freedom, dof, and p= 0.05) overestimation of M_{true}; on the contrary, as expected, using M_{MM} shows in a slightly lower, but not significant, value of M_{true} (paired t-test, t_s= - 0.8 < critical t_s= 1.89 for 7 dof; p= 0.05, Sokal & Rohlf 1981).

Secondly, confirmation to the previously highlighted ambiguity was searched in the information retrieved from literature concerning the symbols and definitions used in the R&E by the authors (Table I). The compilation clearly supports the hypothesis that the age-at-50%-of-maturity instead of the age-at-massive-maturation has been almost generally misinterpreted as the variable *x* in the original R&E.

A generic definition was only employed in Caddy (1980), but he later (Caddy 1991) described the R&E as the expression where "adult M is considered a reciprocal function of the mean age-at-maturity". Some authors have also reported both age-at-sexual-maturity (defined as age at first, or 50%, or mean, sexual maturity) and age-at-massive-maturation, but considered the two terms synonyms. The only acknowledgment that those different parameters were originally analysed was found in Srinath (1998), although that author did not present in his contribution either the symbols or the R&E model. The use of percentage of maturation higher than 50% was found only in Pakhomov (1995), Vasilyev & Belikov (2002), both referring to the Russian version of the R&E (Rikhter & Efanov 1977), and Rikhter (1988). Notwithstanding these specifications, papers published after 2002 keep using a_{m50} instead of a_{MM} (Table I).

Present analysis confirms that the implementation of the R&E has been hampered by the ambiguity in the original paper and it is likely that the higher % of maturity employed by Pakhomov (1995) and Vasilyev & Belikov (2002) reflected the adjustment reported in Rikhter & Efanov (1977) paper, which few other authors have seen because of the language (Russian) in which it was written and its limited distribution. However, already in their original paper in English, Rikhter & Efanov (1976) concluded that the age-at-massive-maturation performed better than the age-at-50%-of-maturity, after a qualitative analysis of goodness of fit and correspondence with independent estimates of M (M_{true}), at least for species in colder waters (see also Butcher & Hagedoorn 2003).

The difficulty in objectively defining "massive maturation" might explain why that parameter has been generally replaced by age-at-50%-of-maturity, with tangible consequences for assessments of population dynamics unless those cases where a_{m50} and a_{MM} result close to each other as a consequence of a high steepness in the logistic ogive and a "faster" growth pattern (i.e. cases for which the age-at-maturity plot approximates a knife-edge profile). Given that a full coincidence between a_{m50} and a_{MM} should be the exception (at least for iteroparous, indeterminate-growing fish) and that the coefficients in the R&E refer to a_{MM}, it is evident that the smaller a_{m50} used in most papers of Table I likely have determined inflated estimates of M.

It is seldom possible to obtain accurate estimates of the natural mortality coefficient in already exploited stocks; Schaefer & Beverton (1963) therefore suggested establishing a range of values within which the true value is likely to lie. In general, all indirect methods for estimating M are even more affected by problems in precision and accuracy, and hence in their predictive power (Roff 1984, Vetter 1988, Gulland & Rosenberg 1992, Pascual & Iribarne 1993, Hoggarth *et al*. 2006, McCoy & Gillooly 2008). Although it is not possible to get direct estimations of the R&E variance (Garcia & Le Reste 1981), quite high coefficients of variation, ranging from 24% up to 57%, were obtained through bootstrapping (Cubillos *et al*. 1999, Cubillos & Araya 2007, Alarcón *et al*. 2011).

The Rikhter & Efanov (1976) paper remains an important historical step in the progress of the fishery science, especially for populations of long living and slow growing/slow maturing species. But most of the present available estimates of M based on the R&E and a_{m50} are overestimated and often make overly optimistic diagnoses of stock exploitation. Given that more recent, less ambiguous alternatives to obtain indirect M estimates are available (Hewitt & Hoenig, 2005, Ragonese *et al.* 2006, Gislason *et al.* 2010, Charnov *et al.* 2012, Siegfried & Sansó 2012), even by applying length or age at maturity (Roff 1984, Jensen 1996, Brodziak *et al.* 2011), it seems that there is no reason to keep using the R&E expression, and it should therefore be recalled.

Table I. Symbols and definitions for the Rikhter & Efanov (1976) expression as reported in literature. Remarks refer to specifications made by the authors or notes arising from the present paper. Contributions presenting neither symbols/expression nor the kind of employed age-at-maturity have been excluded. L_{m50} = length at 50% of maturity; M, M_{m50} and M_{MM} denote generic, based on age-at-50%-of-maturity (a_{m50}; year, yr) and on age-at-massive-maturation (>50%; a_{MM}) instantaneous mortality rate (yr^{-1}), respectively. Taxon: BF, bony fish; CF, cartilaginous fish; CR, crustaceans; CE, cephalopods; BI, bivalves; NS, not specified (generic).

Symbol	Definition	Remarks	*taxon*	Reference
x	Age at massive maturation	Age at which over 50% of the specimens in investigated population are mature	BF	Rikhter & Efanov 1976
t_m	Age at maturity	No further specification	NS	Caddy 1980
tm50	Age when 50% of the population is mature	Authors consider it synonymous with R&E's "age at massive maturation"	NS	Garcia & Le Reste 1981
t_m	Age at which 50% of the population is mature	No further specification	NS	Jones 1984
np	Age at massive sexual maturation	The % of mature was 56.5 at 2 yr and 100 at 3 yr, resulting in M_{M56}= 0.77 and M_{M100}= 0.53; M_{M100} was chosen for this paper	BF	Rikhter 1988
T_m	Age at 50% maturity	"Age at massive maturity" as synonymous of age at 50% of maturity	NS	Brethes & O'Boyle 1990
t_m	Age at 50% maturity of the species	a_{m50}= 0.35 yr; M_{m50}= 3.08; dealing with hermaphrodite prawns	CR	Deshmukh 1990
Tm	Age at first (massive) maturity	a_{m50} 1.9-2.1 yr, resulting M_{m50} 0.80-0.74	CR	Wolff & Soto 1992
t_n	Age at which 70% of individuals mature for the first time	Author quotes the Russian version (1977) of the R&E's paper	CR	Pakhomov 1995
Tm50	Age at which 50% of females are mature	Corresponding to L_{m50}	CR	Wolff & Aroca 1995
t_m	Age at which 50% of the population is mature	a_{m50} about 1 yr	CR	Harikrishnan & Madhusoodana Kurup 1997
T_m50%	Age when 50% of the population is mature	Also called "age at massive maturation"	BF	Kraljević & Dulčić 1997
T_m50%	Age at which 50% of the population was mature	Also called "age at massive maturation"	NS	Sparre & Venema 1998
t_{m50}	Age when 50% of the population mature	"A larger proportion, perhaps 50%, spawn in the 1+ age group"; however, Authors used 2 yr as t_{m50}	BF	Al-Hosni & Siddeek 1999
Tm_{50}	Age of 50% maturity	Coefficient of variation estimated	BF	Cubillos *et al*. 1999
t50%	Age of 50% maturity	Reporting M= 0.59 for a_{m50}= 2.05 yr; however, converting L_{m50} (120 mm) by growth parameters results in a_{m50}= 1.8 yr, hence M_{m50}= 0.84; M_{M100}= 0.57	BF	Hansen 1999
Tm50	Age in which 50% of the population is mature	M_{M100}=0.50 vs. M_{m50}= 0.77	BF	Rueda & Santos-Martínez 1999
t mass	Age at which 50% of females reach the age of "massive spawning"	a_{m50}= 0.5 yr; M_{m50}= 2.35	CE	Arreguín-Sánchez *et al*. 2000
Tm 50%	Age when 50% of the population is mature	M_{m50}= 1.73	CR	Jayawardane *et al.* 2002

Table I continued

T_m(50%)	Age at which 50% of the population was mature	No further specification	NS	Kolding & Ubald Giordano 2002
a_m	Age of "mass" maturity, age in which at least 70% of fish are mature (following the 1977 version)	"Naturally, the estimate is very sensitive to the choice of age of mass maturity"; however, used a_{MM} of 3 yr (82% of mature fish); M_{M86}= 0.405	BF	Vasilyev & Belikov 2002
t_{mat} 50%	Age at 1st maturation	Age at 50% from the symbol	NS	Cadima 2003
t_{mass}	Age of mass sex maturity	2 yr was considered the age at which large number reproduce; M= 0.77	BF	Bradova & Prodanov 2003
T_{m50}	Size at which 50% of the population are mature	"Known as the age of massive maturation"; the reported M= 0.48 corresponds to 3.4 yr, a figure higher than the expected a_{m50}= 1.1	BF	Butcher & Hagedoorn 2003
tm50	Age at 50% of maturity	*Sillago analis*: ♂ 0.84 (M_{m50}) vs. 0.65 (M_{M95}); ♀ 0.74 (M_{m50}) vs. 0.59 (M_{M95}) - *Sillago schomburgkii:*♂ 0.88 (M_{m50}) vs. 0.71 (M_{M95}); ♀ 0.65 (M_{m50}) vs. 0.46 (M_{M95})	BF	Coulson 2003
t_{m50}	Mean age of first maturity	Compared with other methods, R&E resulted in higher estimates; "o valor resultante de tal método pode não ser o mais acertado"	BF	Velasco *et al*. 2003
t_{mass}	Age of massive maturation	Not specified. M = 0.96 corresponding to 1.5y	BF	Mehanna 2004
Tm50%	Age when 50% of the population is mature	Also called "the age of massive maturation"	NS	Srinath 2004
t_{mat}	Age at maturity	Not specified, likely age at 50% by comparing FishBase	CF	Cortés & Brooks 2005
t_{mass}	Age at which 50% of the stock reaches the age of "massive spawning"	Implemented in FiSAT software (the model should not be used for tropical stocks); symbol and definition contrast each other	NS	Gayanilo *et al*. 2005; FiSAT users: Perez Lizama & Ambrosio 2004, Rizvi *et al*. 2005, Naranjo 2011
t_m	Age of 50% maturity	Also called "age at massive maturation"	NS	Ragonese *et al*. 2006
T_m	Age at sexual maturity	Mean age (50%) at maturity; coefficient of variation estimated	BF	Cubillos & Araya 2007
t_{mass}	Age at which sexual maturation is attained	Age at 50% of maturity (2 yr) as input	BF	Grandcourt *et al*. 2007
Tm50%	Median age at maturity	Age at first maturity, i.e. 50% of the population is mature. M_{MM} was 0.25-0.36 vs. 0.30-0.38 of M_{m50}	BI	Jaramillo (resp.) 2008
$t_{m\ 50\%}$	Age at 50% of maturity	No further specification. M_{M100}= 0.84 vs. M_{m50}= 1.30	BF	Canales & Leal 2009
T_m	Age at maturity	Estimated by age at 50% maturity; coefficient of variation estimated; M_{MM}= 0.38-0.25 vs. M_{m50}= 0.50-0.32	CF	Alarcón *et al*. 2011
t_m	Age at maturity	Age at which 50% of the stock reaches the age of "massive spawning"; the two definitions are considered synonymous	BF	Jarić & Gačić 2012
t_{mass}	Age in years when 50% of the stock is mature	Authors quote the Russian version (1977) of the R&E's paper	NS	Siegfried & Sansó 2012

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