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Composite per-recruits: Alternative metrics for deriving biological reference points of fishery resources

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HIGHLIGHTS

- Composite per-recruits expand on fisheries delay-difference models.
- The CYPR–CSPR method is a new type of per-recruit analyses.
- CYPR14 peaks at F_{MSY} that has the greatest accuracy about F_{MSY} of most data-rich stocks.
- CYPR14 is recommended for devising MSY biological reference points of data-poor stocks.

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ABSTRACT

Most exploited aquatic populations lack the fishery selectivity and life-history information, by age/size, needed to develop harvest control rules (HCRs). This study relies on stage-structured life-history and fishery characteristics inherent in delay-difference models to set out a typology of composite (age-aggregated) yield per-recruit (CYPR) models along with composite spawning stock per-recruit (CSSR) models and composite spawning per-recruits (CSPRs) and propose the related, conventional-like biological reference points, which may prove useful in devising HCRs, especially for data-poor stocks. CYPR, CSSR, and CSPR are equilibrium and interrelated metrics controlled by fishing mortality. Inputs to their development include growth and natural mortality parameters and, eventually, stage-specific selectivity, natural mortality, and maturity. In spite of numerous formulations of CYPRs denoted CYPR1 to CYPR15, CYPRs fall into three types of equations following from the Leslie–DeLury depletion model family for open populations (prototype: CYPR3), the Deriso–Schnute delay-difference model family (prototype: CYPR9), and some differential forms of the previous two model families (prototype: CYPR14). CYPR3, CYPR9, and CYPR14 exhibit, respectively, patterns increasing monotonically toward asymptotes and dome-shaped patterns which, beyond their maxima, trend toward the mean weight-at-recruitment and zero. Comparisons of fishing mortality-based biological reference points (F_{BRP}s) from CYPRs and CSPRs with the fishing mortality producing the maximum sustainable yield (F_{MSY}) or F_{MSY} proxies from 53 data-rich stock assessments on the US East Coast indicate that some F_{BRP}s are accurate estimators of F_{MSY} or F_{MSY} proxies. CYPR14 is the recommended CYPR for determining the plausible sustainability status of data-poor stocks because it accommodates more growth parameters, maximizes at a fishing mortality rate that qualifies for F_{MSY} and has the greatest accuracy about F_{MSY} for the majority of data-rich stocks. Composite per-recruit models should be used in stage-structured model assessments in the same way that conventional per-recruit models are used in age- and length-structured model assessments.

1. Introduction

Contemporary fishery management strategies include BRPs[1] (Caddy and Mahon, 1995). Typically, BRPs are state indicators aimed at setting harvest-control rules. They are designed with the prospect that, under average conditions, yield and spawning stock biomass or the number of spawners will be sustainable. Nonetheless, BRPs such as the benchmarks based on MSY are data demanding and require sophisticated procedures characteristic of contemporary stock-assessment methods of population dynamics (Shepherd, 1982; Kimura et al., 1984; Prager, 1994; Hart, 2013). Unfortunately, MSY-based prescriptions, especially those from nominally data-rich stock-assessment models, are seldom trustworthy, largely because they follow from unreliable and

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[1] HCR: Harvest control rule; BRP: Biological reference point; SRR: Stock–recruitment relationship.

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nonrobust recruit–spawner relationships. Therefore, in practice, BRPs based on age- or length-structured per-recruit models are commonly used as proxies of MSY-based BRPs for both data-rich stocks (Vaughan et al., 2007; Dick and MacCall, 2011; NMFS, 2011; Legault and Brooks, 2013; Rothschild, 2015) and data-limited stocks, for which conventional methods are inapplicable (e.g., Ault et al., 2008 and Hordyk et al., 2015b). The mandates and needs to manage sustainably data-limited fisheries in various jurisdictions have also prompted the development and performance evaluations of many BRPs/HCRs requiring minimal fishery data, life history parameters, or both (e.g., Beddington and Kirkwood, 2005; Dick and MacCall, 2011; Wiednmann et al., 2013; Carruthers et al., 2014).

Traditional per-recruit analyses require selectivity (inferred from data-rich assessment outputs), maturity, and fecundity by age or length. When this information is unavailable and stocks are partitioned into prerecruited (invulnerable to the fisheries) and recruited (fully vulnerable to the fisheries) stages consistent with parameterizations and assumptions of delay-difference population dynamics (e.g., Dichmont et al., 2003; Smith and Addison, 2003; Kahn and Helser, 2005; Ives and Scandol, 2007 for invertebrates; Collie and Sissenwine, 1983; Kimura et al., 1984; Butler et al., 2003; Restrepo and Pallarés, 2003; Jensen et al., 2009; Takade, 2010 for bony fishes; Bonfil, 2005 for elasmobranchs), composite (i.e., age-aggregated) yield per-recruits (CYPRs) and composite spawning stock per-recruits (CSSRs) can be useful for guiding precautionary management (Munyandorero, 2012a,b).

CYPRs and CSSRs are equilibrium and interrelated holistic metrics that expand on delay-difference models. They are composite because, consistent with equilibrium forms of delay-difference models, they follow from the ratio Φ of a multiple-age and fully selected stock size (i.e., total number of individuals or total biomass units) to the recruitment (in numbers); the recruitment itself usually is a mixture of fast-growing individuals from younger cohorts and slow-growing members of older cohorts. With regard to the majority of parent delay-difference models, the CYPR is the exploitation fraction (E^*; $E^* = $ catch/stock size) times Φ, and the CSSR is the whole ratio Φ; according to a few variants of delay-difference models, the CSSR is the ratio Φ adjusted by accounting for likely spawners (Miller et al., 2011; Munyandorero, 2012a,b; GDAR, 2013; Sutton et al., 2014). Furthermore, similar to the calculation of the static spawning per-recruit (i.e., SPR not based on egg production) (Goodyear, 1993; Gulf of Mexico SPR Management Strategy Committee, 1996), the fished CSSR to unfished CSSR ratios give the composite spawning per-recruits (CSPRs). CYPRs and CSSRs depend on fishing mortality (F) as a control variable and on growth parameters and natural mortality (M) as inputs.

Because CYPR (and CSSR) models are rooted in delay-difference models (Munyandorero, 2012a,b), they inherit the assumptions of these models (e.g., knife-edge recruitment, knife-edge selection, constant mortality rates, constant growth rates where appropriate, equal reproductive capacity for all survivors). These assumptions bring CYPR (and CSSR) models closer to the Beverton–Holt per-recruit models (Beverton and Holt, 1957; Munyandorero, 2001). Regardless, as shown below in Section 2.4.1, CYPR (and CSSR) models have unique patterns and properties.

The ratio Φ from the Deriso (1980) and Schnute (1985) delay-difference model has perhaps been the first type of ratio Φ to be applied (Kimura et al., 1984; Kimura, 1985, 1988; Hilborn and Walters, 1992). These authors did not call Φ the "spawning stock biomass per-recruit (SSBR)" but noted its analogy with the age- and length-structured SSBRs. Similar to Beverton and Holt (1957, Eq. (6.23)) and Shepherd (1982), they therefore combined Φ with SRRs to develop the equilibrium (or "self-generating") biomass and yield functions of F and to estimate MSY-based benchmarks. The ratios Φ that have been developed recently follow from various delay-difference models as indicated by Miller et al. (2011), Munyandorero (2012a,b), Carruthers et al. (2012, 2014) and GDAR (2013) and R. Ahrens and C. Walters (R. Ahrens, University of Florida, USA, rahrens@ufl.edu; Personal communication). These contemporary authors referred to Φ as the biomass or the number of spawners per-recruit.

Given management parameters (MSY, E^*_{MSY}, or an F producing MSY, i.e., F_{MSY}), Carruthers et al. (2012, 2014), R. Ahrens and C. Walters (R. Ahrens, Personal communication) and, implicitly, Martell and Walters (2008) and Martell et al. (2008) focused on evaluating Φ at E^*_{MSY} or at F_{MSY} as a prerequisite for deriving the classical stock–recruitment parameters (i.e., maximum recruits per spawner as spawner abundance approaches zero and the degree of compensation). In contrast, Miller et al. (2011), Munyandorero (2012a) and GDAR (2013) used Φ similarly as Kimura et al. (1984), Kimura (1985), Kimura (1988) and Hilborn and Walters (1992) and, for the first time, developed the associated yield per-recruits (YPRs). Moreover, GDAR (2013) and Sutton et al. (2014) calculated the current SPR at current F, while Munyandorero (2012a,b) first referred to such YPRs as composite YPRs (CYPRs). Munyandorero (2012a,b) also noted that CYPRs and Φ relate to each other and are characteristic of delay-difference models. Unlike Miller et al. (2011), Carruthers et al. (2012, 2014), GDAR (2013) and Sutton et al. (2014) he demonstrated that the CYPRs and Φ can be associated with F levels that could be useful as proxies for F_{MSY}.

Munyandorero (2012a,b) introduced the composite per-recruit metrics, but his work was not focused on CYPR and CSSR variants/types, properties, and potential to generate BRPs. Essentially, he pointed out some CYPRs and framed their general patterns only. The present study therefore aims to complement Munyandorero (2012a,b). Its primary goals are to:

(i) Document the CYPR (and CSSR) functions and set out a classification of these functions on the basis of similar formulations and patterns (i.e., variations of CYPR and CSSR with F) including critical points;
(ii) Propose a framework for developing BRPs from CYPRs and CSPRs.

In addressing these objectives, it is deemed essential to expand on the basics (including discussions of theoretical properties) of CYPRs and CSSRs, because these metrics are recent in the literature.

The performance of CYPRs and CSPRs is evaluated, for illustration purposes only, for 53 data-rich stocks off the US East Coast, from the Gulf of Mexico to the Gulf of Maine (Table 1 for fish; the specifications for one invertebrate investigated, the blue crab *Callinectes sapidus* in the US Gulf of Mexico, are described separately). F_{MSY} or F_{MSY} proxies derived from these stocks' most recent (benchmark or update) assessments are compared with F-based BRPs (F_{BRP}s) associated with CYPRs and CSPRs. Results from various CYPRs and CSPRs are detailed for the bluefish (*Pomatomus saltatrix*) stock off the US Atlantic coast and the blue crab stock in the US Gulf of Mexico. For other stocks, only results from CYPRs identified as prototypes of CYPR categories are presented.

2. Methods

2.1. CYPR and CSSR: background

Various published fisheries delay-difference models are first compiled (Table 2 for symbols and Table 3 for model sources). These models are defined as time-series (discrete or continuous/differential), two-stage-structured population dynamics equations, parameterized in numbers of individuals or in biomass units, ranging from simple depletion models (e.g., Collie and Sissenwine, 1983) to more complex formulations (e.g., Hilborn and Walters,