Fisheries Research xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Short communication

How should fishing mortality be distributed under balanced harvesting?

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ARTICLE INFO

Handled by A.E. Punt

Keywords:
Ecosystem approach to fisheries
Ecosystem-based fisheries management
Holling-tanner model
Multi-species harvest strategies
Productivity
Trophic structure

ABSTRACT

Zhou and Smith (2017) investigate different multi-species harvesting scenarios using a simple Holling-Tanner model. Among these scenarios are two methods for implementing balanced harvesting, where fishing is distributed across trophic levels in accordance with their productivity. This note examines the effects of a different quantitative implementation of balanced harvesting, where the fishing mortality rate is proportional to the total production rate of each trophic level. The results show that setting fishing mortality rate to be proportional to total production rate, rather than to productivity per unit biomass, better preserves trophic structure and provides a crucial safeguard for rare and threatened ecological groups. This is a key ingredient of balanced harvesting if it is to meet its objective of preserving biodiversity.

1. Introduction

Balanced harvesting (BH) is a proposed approach to fishing, which "distributes a moderate mortality from fishing across the widest possible range of species, stocks, and sizes in an ecosystem, in proportion to their natural productivity" (Garcia et al., 2012). BH was developed as a strategy to conserve biodiversity and ecosystem function, consistent with the concept of ecosystem-based fisheries management (Zhou et al., 2010). Among the hypothesised benefits of BH are improved biodiversity conservation, reduced disruption of community structure, increased resilience to fishing and increased biomass yields (Law et al., 2012; Charles et al., 2015; Garcia et al., 2015). BH has been criticised as being difficult to implement, implying the harvest of species of conservation concern such as seabirds and marine mammals, and reducing economic profits from fishing by shifting catches towards species and/or sizes with low market value (Burgess et al., 2015; Froese et al., 2015; Pauly et al., 2016; Reid et al., 2016). Scientific studies can help us to understand the consequences of alternative fishing policies and harvest rules. Assessing the relative value of those outcomes involves a complex set of trade-offs among ecological, economic and societal values, and is ultimately a sociopolitical judgement rather than purely a scientific one. However, this judgement needs to be informed by the best possible scientific evidence and mathematical models have an important role to play in this.

BH has been studied using size-based community models (Law et al., 2012, 2015; Jacobsen et al., 2014; Kolding et al., 2015) and using multi-species ecosystem models, such as Ecopath and Atlantis (Bundy et al., 2005; Garcia et al., 2012; Kolding et al., 2016; Heath et al., 2017). These studies have shown that BH has the potential to maintain or increase total sustainable ecosystem yield, albeit consisting of a greater proportion of species and sizes of low commercial value, while better preserving ecosystem structure. However, these models are relatively complex and their results may be sensitive to model assumptions or noisy data. On the other hand, simple models can sometimes offer qualitative insights that more complex models cannot. Given the controversy generated by BH, it is appropriate that its consequences be investigated using a range of different modelling approaches (Garcia et al., 2014).

Zhou and Smith (2017) investigate the effects of various types of selective or non-selective fishing in a simple, equilibrium Holling-Tanner model (Tanner, 1975) of a fish community split into three trophic levels (TLs). In this model, a fishing scenario must specify not only the overall intensity of fishing, but also how fishing mortality is distributed across TLs. Among the fishing scenarios considered by Zhou and Smith (2017) are two forms of BH, in which fishing mortality rate F is proportional either to the current productivity or to the maximal productivity of each TL. Productivity is defined as the amount of new biomass produced per unit of existing biomass per unit time, with dimensions time^{-1} (Garcia et al., 2012) and denoted P/B in Ecopath models (Christensen and Pauly, 1992). Maximal productivity is the productivity at close-to-zero biomass, which, under the assumptions of the Holling-Tanner model, is equivalent to the intrinsic rate of increase, r. These two fishing scenarios are referred to as $F \sim P/B$ and $F \sim r$, respectively.

Zhou and Smith (2017) calculate the biomass, yield and disruption of trophic structure resulting from each fishing scenario examined and show that the only scenario that perfectly preserves trophic structure is fishing exclusively on the lowest TL (representing planktivorous fish).

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https://doi.org/10.1016/j.fishres.2018.06.003
Received 16 April 2018; Received in revised form 5 June 2018; Accepted 6 June 2018

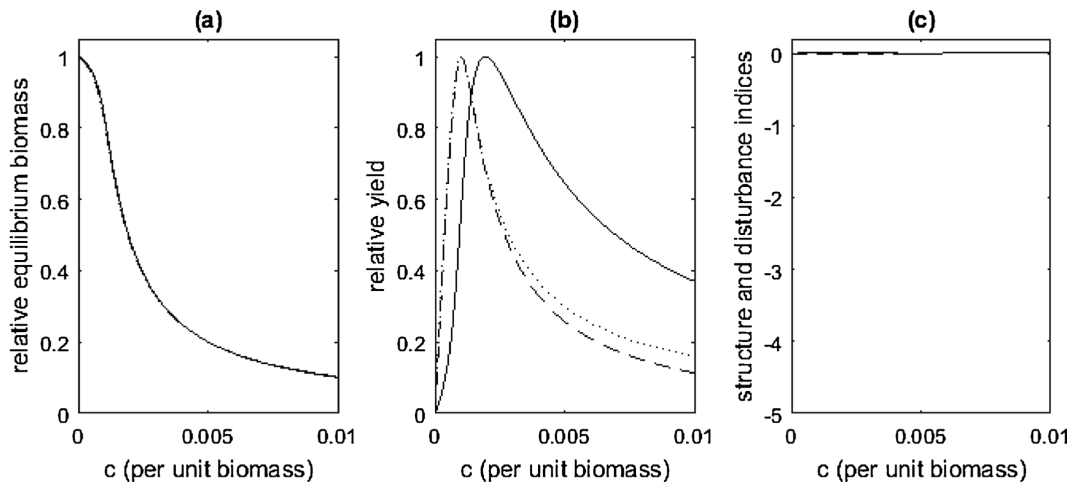

Fig. 1. Equilibrium biomass, yield and trophic structure for fishing proportional to production rate ($F_i = cP_i$): (a) equilibrium biomass relative to maximum; (b) yield relative to maximum (TL1 solid, TL2 dashed, TL3 dotted); (c) slope of log biomass-TL relationship (dashed) and disturbance index (solid).

The reason is that, under the assumptions of the Holling-Tanner model, the biomass depletion of the lowest TL is transmitted up the food chain, causing proportional biomass depletions of the unfished higher TLs. The obvious downside to this fishing scenario is that the catch is exclusively from the lowest TL, which may not be economically desirable. In contrast, both forms of BH examined by Zhou and Smith (2017) ($F \sim P/B$ and $F \sim r$) provide a catch composed of all three TLs and a higher total yield. However, both scenarios also cause significant disruption to the trophic structure, with disproportionate depletion of the higher TLs. In addition, under fishing with $F \sim P/B$, there is a sudden collapse of all three TLs as the exploitation ratio (ratio of yield to production rate, which is the control parameter in setting $F \sim P/B$) is increased from 0.85 to 0.95.

An alternative strategy for BH, not considered by Zhou and Smith (2017), is to set the fishing mortality rate F to be proportional to the total production rate P of each TL (dimensions mass × time^{-1}). This strategy has been investigated previously in size-spectrum models (Law et al., 2015). A key feature of this approach is that it incorporates a density dependence into the fishing mortality rate. This means that, as an ecological group, such as a species or TL, becomes depleted and its total production rate drops, the fishing mortality rate on that group is automatically reduced. Since, in an equilibrium model, yield Y is equal to fishing mortality rate F multiplied by biomass B, fishing with $F \sim P/B$ is equivalent to setting a constant exploitation ratio (Y/P) across all TLs (Kolding et al., 2016). Fishing with $F \sim P$ means that $Y \sim PB$, so this calls for a higher exploitation ratio on TLs with higher biomass (Heath et al., 2017). This note investigates the effect of BH with $F \sim P$ in the model considered by Zhou and Smith (2017).

2. Methods

The Holling-Tanner model considered by Zhou and Smith (2017) is defined by the following differential equations for the biomass B_i of TL i (i = 1, 2, 3):

$$\frac{dB_i}{dt} = r_i B_i \left(1 - \frac{B_i}{K_i}\right) - M_i B_i - F_i B_i, \quad (1)$$

where r_i is the intrinsic growth rate, K_i is the carrying capacity, M_i is the natural mortality rate and F_i is the fishing mortality rate of TL i. The carrying capacity of TL1 is constant. The carrying capacities of TL2 and TL3 are given by $K_i = e_{i-1,i} B_{i-1}$, where $e_{i-1,i}$ is the efficiency of biomass transfer from TL $i-1$ to TL i. The natural mortality rates for TL1 and TL2 are given by a type-II function of predation by the TL above: $M_i = \frac{p_{i,i+1} B_i B_{i+1}}{D_i + B_i}$. The natural mortality rate for TL3 is constant. All parameter values are the same as those used by Zhou and Smith (2017).

To set the fishing mortality rate in proportion to the production rate ($F \sim P$), define

$$F_i = c r_i B_i \left(1 - \frac{B_i}{K_i}\right), \quad (2)$$

where c is a constant controlling the overall level of fishing intensity. Under the scenarios considered by Zhou and Smith (2017), overall fishing intensity is controlled by a constant of proportionality f that is dimensionless and can be varied between 0 and 1. The constant c in Eq. (2) has dimensions mass^{-1} and does not have an a priori defined range. Values of c are trialed in the model to find an appropriate range encompassing the maximum sustainable yield for each TL.

The differential equations, Eq. (1), for each TL are solved numerically until an equilibrium is reached. The equilibrium (i.e. sustainable) yield for TL i is calculated as $Y_i = F_i B_i$. Following Zhou and Smith (2017), disruption of trophic structure is measured in two ways: (i) the slope of the relationship between TL and log biomass; (ii) the disturbance index (DI), which is based on biomass ratios of adjacent TLs (Bundy et al., 2005). This process is repeated for a range of values of the constant c that determines the overall intensity of fishing.

3. Results

Fig. 1 shows the effect of fishing in proportion to production rate ($F \sim P$) on the relative biomass and yield of each TL (compare with Figs. 1–6 of Zhou and Smith, 2017), for values of the overall fishing intensity c ranging from 0 to 0.01 per unit biomass. Fig. 2 shows the total ecosystem biomass and yield against average fishing mortality rate F (compare with Fig. 7 of Zhou and Smith, 2017). For comparison, Fig. 2 also shows the two BH scenarios examined by Zhou and Smith (2017) and the scenario where fishing is only on TL1. From these results, several observations are possible for this simple model:

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1 Fishing with $F \sim P$ preserves trophic structure almost perfectly (the three TL biomass curves are almost indistinguishable in Fig. 1a, and the slope and DI are barely affected by fishing in Fig. 1c). This is mainly because this strategy focuses most of the fishing on the lowest TL, where the production rate is highest. As with the strategy of fishing only the lowest TL, the biomasses of the higher TLs are depleted in proportion as a result of reduced carrying capacities. These TLs have relatively low biomasses and hence production rates so, under $F \sim P$, they are subjected to relatively low fishing mortality rate. This protects them from the disproportionate biomass depletions that they suffer under $F \sim P/B$.