THE MARINE TROPHIC INDEX (MTI), THE FISHING IN BALANCE (FIB) INDEX AND THE SPATIAL EXPANSION OF FISHERIES[1]

Kristin Kleisner and Daniel Pauly
Sea Around Us *Project, Fisheries Centre, University of British Columbia*
2202 Main Mall, Vancouver BC V6T1Z4 Canada

ABSTRACT

The Marine Trophic Index (MTI), used by the Convention of Biological Diversity (CBD) as an index of marine biodiversity has been recently shown to display increases in the absence of recovery of traditionally exploited high-trophic level groups. This is interpreted here as the result of the spatial expansion of fisheries, as can be demonstrated by widespread increases of the Fishing-in-Balance (FiB) Index, which can be re-interpreted as an indicator of spatial expansion. We show that it is possible to modify the MTI such that it explicitly accounts for the spatial expansion. This leads to a new index, the Fisheries Sustainability Index (FSI), the potential utility of which is briefly discussed with reference to Regional Seas.

INTRODUCTION

Globally, fisheries are in decline, mainly due to overfishing, with pollution and habitat degradation, and possibly global warming, adding to the stresses. However, defining indicators that reflect the state of fisheries is often challenging, especially in data-sparse contexts. The Convention of Biological Diversity's (CBD) Marine Trophic Index (MTI) was developed, based on the contribution of Pauly *et al.* (1998), on the assumption that a decline of the mean trophic level of fisheries catch (mTL=MTI) is generally due to a fisheries-induced reduction of the biomass and hence biodiversity of vulnerable top predators. The MTI tracks changes in mean trophic level (mTL), defined for year *k* as:

$$mTL_k = \sum(Y_{ik} \cdot TL_i) \;/\; \sum(Y_{ik}) \qquad \ldots 1)$$

where Y_{ik} is the catch of species i in year k, and TL_i the trophic level of species (or group) i, the latter usually obtained from the diet composition studies in FishBase (www.fishbase.org).

Usually, mTL (and hence, the MTI) declines as the result of fishing pressure being focused on the higher trophic levels at the start of the fishery, which is then replaced by pressure on the lower trophic levels as the abundance of high trophic level species declines. Therefore, the MTI can be seen as an index of the biodiversity of the top predators (Appendix 9). The occurrence of 'fishing down marine food webs' (FDMW) was initially documented globally using FAO landings data from 1950 to 1994, combined with estimates of trophic levels extracted from 60 published mass-balance trophic models from every major aquatic ecosystem type (Christensen and Pauly, 1993; Pauly and Christensen, 1993; Christensen, 1995; Pauly and Christensen, 1995). Since it was first proposed in 1998, the notion that we are 'fishing down' has been largely validated through numerous studies on a large number of marine and freshwater ecosystems (see, e.g., Jackson *et al.*, 2001; Worm and Myers, 2003; Bellwood *et al.*, 2004; Hutchings and Reynolds, 2004; Frank *et al.*, 2005; Scheffer *et al.*, 2005; Morato *et al.*, 2006), and it has been straightforward to fend off its earlier critics (Pauly, 2010). However, several recent studies demonstrate that a downward MTI trend can be masked when a geographic expansion of the fisheries of a given region or country has occurred, which enables them to maintain or even augment their catch of high-trophic level species.

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The effect of geographic expansion on the trophic level of catch was first analyzed with an index called Fishing-in-Balance (FiB; Appendix 10). This index was developed to address what may occur when the decline in mTL is attributable to the deliberate choice of targeting low trophic level species. In this case, one might assume that fishers may choose to fish lower in the food web because biological production is higher at lower trophic levels (Pauly *et al.*, 2000). If the choice to fish lower in the food web is deliberate, one would expect there to be an increase in the catch that is commensurate with the decline in mTL. This leads to the development of the FiB (Pauly *et al.*, 2000b), defined for any year *k*:

$$\text{FiB} = \log(Y_k \cdot (1/\text{TE})^{\text{mTL}_k}) - \log(Y_o \cdot (1/\text{TE})^{\text{mTL}_o}) \quad \ldots 2)$$

where *Y* is the catch, *TL* is the mTL in the catch, *TE* is the transfer efficiency between trophic levels, and o refers to the year used as a baseline. The FiB is calculated with the geometric mean of each of the terms thereby preserving the relationship between equivalent amounts of fish at different trophic levels. Therefore, this index should:

- remain constant (=0) if the fishery is 'balanced', i.e., all trophic level changes are matched by 'ecologically equivalent' changes in catch;
- increase (>0) if there are (a) bottom-up effects (e.g., an increase in PP, as described above and in Caddy *et al.*, 1998), or (b) geographic expansion of the fishery to new waters which in effect expands the ecosystem exploited by the fishery; or
- decrease (<0) if discarding occurs that is not represented in the catch, or if the ecosystem functioning is impaired by the removal of excessive levels of biomass.

The FiB is an index, which, as proposed, was meant to be viewed jointly with the MTI, whose interpretation it was supposed to facilitate. However, few if any authors account for changes in the FiB index when they examine trends in mTL. If they did, they would notice that generally, mTLs fail to decline in regions where the FiB index increases (see MTI and FiB trends for all maritime countries and Large Marine Ecosystems of the world at www.seaaroundus.org).

Butchart *et al.* (2010) and Sethi *et al.* (2010) reported that for many regions, and for the world ocean as a whole, mTLs, while declining from the 1950s to the early 1980s, have tended to increase in the 1990s and 2000s. As there is no independent evidence that high trophic level fish populations have been rebuilt throughout the world, we must conclude that either:

1. the mTL of fisheries catches cannot be used as indicators of fisheries impacts on biodiversity because trophic levels may change in unpredictable fashion, or similar *ad hoc* explanation; or
2. the mTL can detect fishing down reliably, but only after accounting for one or several 'hidden variables'.

We present the case for (2) and suggest that the 'hidden variable' is the spatial expansion of fisheries from the late 1980s to the 2000s.

Methods for Correcting for Geographic Expansion

Spatial considerations are relatively easy to incorporate into the trophodynamic considerations underlying FDMW and the FiB index. Ecosystems may be conceived as biomass flow pyramids whose base is proportional to the amount of primary productivity in the system, and the top angle is related to the transfer efficiency between trophic levels. Such pyramids, when exploited (say from the top down), imply that a relatively small catch is available at higher trophic levels and larger catches at lower trophic levels, with the mTL of the catch providing an indication of a fishery's position.

Thus, as presented before for the FiB index, when a fisheries exploits a given area (and pyramid), the catch should increase when mean trophic level of the catch decreases and *vice versa*, the relationship between these two quantities being mediated by the transfer efficiency (TE) between trophic levels (i.e., the slope of the pyramid). However, when the catch increases more than is compatible with the observed change in trophic level, this suggests that, in effect, another adjacent pyramid is being exploited, i.e., that the fisheries has expanded (and conversely for a decline in catch not matched by a simultaneous increase in mTL, suggesting that a contraction of fisheries has occurred). The key assumption here is that 'adjacent pyramids' have the same productivity. This assumption obviously does not hold in reality. However, it can be assumed that fisheries are generally initiated in areas of relatively high productivity (e.g., inshore), and then move into areas of lower productivity (e.g., offshore). Therefore, the assumption of equal productivity would generally lead to an underestimation of spatial expansion (see Bhatal and Pauly, 2008). Thus, we can derive the mTLs, which would be realized if geographic expansion had not occurred. The main assumptions for this are:

- Spatial expansion and contraction of fisheries do in fact occur, i.e., the increase in the FiB is not due to other factors (such as bottom-up effects); and
- FiB remains at 0 when there is no expansion or contraction of the fisheries.

The computations involved here consist of solving the FiB for the trophic level that would have been realized if geographic expansion had not occurred, then using that difference to correct the MTI. Therefore, equation (2) can be used to define, for any year *k*, a stationary mean trophic level where we have corrected for expansion (mTL_{stat}) where:

$$mTL_{stat} = mTL_o - \log(Y_k/Y_o) \qquad \ldots 3)$$

This correction factor is then subtracted from the mTL in a given year and the absolute value of this difference used to express a 'Corrected Trophic Index' (CTI):

$$CTI_k = mTL_k - |mTL_k - mTL_{stat}| \qquad \ldots 4)$$

The absolute value of the difference is necessary because FiB can fluctuate in both the negative and the positive direction from the first year (chosen arbitrarily as 1950, the first year of the time series in this case), and it is the *magnitude* of this difference that we are correcting for. Finally, we define a new 'Fishing Sustainability Index' (FSI), which is simply the CTI re-expressed in standard deviation units, so that the ordinate scale indicates change without reference to absolute trophic levels. This latter point is necessary given that CTI values can be very low, even negative, which would not be accepted by most users, even by those who understand that CTI values reflect a hypothetical situation (i.e., the mTL a fishery would have if it had not expanded). Thus, we have, finally:

$$FSI = (CTI_k - A_{CTI})/SD_{CTI} \qquad \ldots 5)$$

where CTI_k is the CTI in a given year *k*, A_{CTI} is the average of the CTI, and SD_{CTI} is the standard deviation of the CTI.

Results and Discussion

We demonstrate the ability of the FSI to account for the historical expansion and contraction of fisheries with an example from the waters of Australia. Fishing in Australia has provided an important source of protein for aboriginal people in the country for many centuries and for European settlers since the late 18th century. Modernization of fishing fleets in the 1960s allowed for the expansion of Australian fishing vessels into deeper waters further from shore; the FiB index has thus increased (Figure 1, upper right). From 1950 to about 1970, catches were relatively flat, and the MTI declined, indicating 'fishing down' in inshore waters. For this period, the FiB index indicates that the fisheries were, in a sense, 'balanced'. It is not until the period of rapid geographic expansion in the 1970s that the MTI begins to increase. This increasing trend, which is due to geographic expansion, is precisely what the FSI corrects for. In this case, the FSI

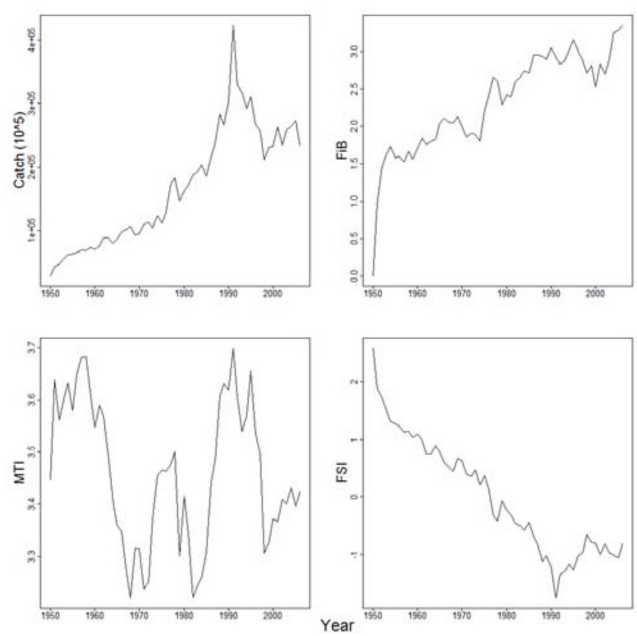

Figure 1. Trends in catch (upper left panel); Fishery in Balance Index (FiB; upper right): Marine Trophic Index (MTI; lower left); and Fisheries Sustainability Index (FSI; lower right) for the Australian EEZ (see text for interpretation).

indicates that had geographic expansion not allowed for tapping into a previously unexploited, high-trophic level fish community, the MTI would have continued the decline it featured in the 1950s and 1960s.

Based on the newly defined FSI, it is suggested that the increasing trends in MTI occurring in some regions since the 1980s are mainly due to geographic expansion of the fisheries. As this expansion reaches its limits, we expect that landings will decrease more rapidly, and that 'fishing down' effects will become more obvious in Regional Seas and the world ocean.

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