Quantifying the effect of vessel interference on catch rates: A theoretical approach

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\textbf{A B S T R A C T}

In response to a vessel buyback scheme in a major Australian Commonwealth fishery, nominal catch-per-unit-effort (CPUE) showed dramatic increases. These led to a discontinuity in the statistically standardised CPUE time series, which may also suggest a discontinuity in the relationship between catch-per-unit-effort and abundance. We hypothesise the discontinuity in CPUE is due to reduced vessel interaction effects. Vessel interactions can arise due to, for example, competition or information sharing, and as such can influence CPUE independent of the underlying fish abundance. Thus there remains a need to quantitatively understand the nature of the effect of vessel interactions on CPUE. Awareness of such interactions is common, yet it has not been described in the context of rapid changes of effort brought about by management interventions such as a vessel buyback. Here we focus on vessel interference, ecologically defined as a depression in foraging (catch) rate with increased foraging (fisher, or vessel) density. We present a mechanistic model incorporating a vessel interference term, that could explain situations where CPUE is more responsive to effort buybacks than if vessel interference is assumed. Our hypothesis is that vessel interference makes CPUE a nonlinear function of effort. We define an interference term that interacts with stock dynamics and catchability. Under a simulated buyback, the trajectories of abundance and CPUE change in a manner dependent on the magnitude of the interference. Our simple model of the non-linear effect of vessel interference holds up well under a large range of values for biological and operational parameters. The effect of interference also appears independent of stock carrying capacity, vessel numbers, and the magnitude of relative reduction in vessel numbers. We conclude that our model provides a promising approach to the technically challenging problem of estimating relative abundance under conditions of sudden changes in fishing effort, and thereby improving sustainable fisheries management via appropriate levels of control rules set in response to such estimates.

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1. Introduction

The most common assumption made about the relationship between fishing effort $E$, the abundance of a targeted stock $N$, and catch $C$ is that catch is a linear function of both, so that $C = qN$ (where $q$ is catchability), and consequently Catch Per Unit Effort CPUE $= qN \propto N$. If this really is the case, then intuition suggests that when effort is reduced on a heavily exploited population, the population will generally increase and the CPUE would also increase (for fixed $C$ and $q$). Conversely, if effort is increased, then CPUE would be expected to decline.

The Southern and Eastern Scalefish and Shark Fishery (SESSF) in Australia (Smith and Smith, 2001; Smith et al., 2008) experienced management intervention via a vessel licence buyback scheme in 2005/2006. This resulted in a 40% reduction in the trawl fleet, and a 16% reduction in non-trawl vessels (Vieira et al., 2010). The buyback was enacted in response to a lack of profitability that had been impacting fishing practices, and quota transfers. The total allowable catch (TAC) remained unchanged during the buyback: the notion was that increased profitability would be achieved by distributing the same catch among fewer vessels.

In some cases, such as for flathead (Neoplatycephalus richardsoni), nominal CPUE showed dramatic increases as a result of the reduction in vessel numbers (Sporcic and Haddon, 2015) increasing by 25.6% from 2005 to 2006 and by 40.8% from 2006 to 2007, and then stabilizing over the next five years. Moreover, standardised CPUE (which is used in SESSF stock

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assessments via generalised linear models to obtain a relative abundance estimate trend), did not appear to adequately account for the factors contributing to these increases (while noting that co-incident factors such as increased recruitment, or increased availability due to environmental conditions, cannot be ruled out as having been responsible): following the reduction in vessel numbers, there remained a discontinuity in the standardised CPUE time series about the time of the buyback. That is, the standardised CPUE did not adequately decouple the relationship between stock abundance and confounding variables.

Vessel interaction effects have been identified and acknowledged more broadly (e.g. Gillis, 1999). Dreyfus-Leon and Gaertner (2006) considered information sharing between fishers in the context of a neural network model, and showed that performance decreased at bigger group sizes, probably due to competition and depletion effects of some fishing grounds.

Rijnsdorp et al. (2008) examined competition effects in the Dutch demersal fishing fleet and found that in the ten years following the introduction of the beam trawl in the 1960s, a decline in catchability, attributed to vessel competition, was observed in beam trawlers used for reference measurements. Gillis et al. (2006) suggested that increasing fleet size may have a disproportionately small impact on fishing mortality because of limitations in information exchange.

Rijnsdorp et al. (2000a) inferred that declines in catch rate over 48 h may be in part due to interference competition among vessels. Rijnsdorp et al. (2000b) found that catch rates of vessels that continued fishing during a week in which a segment of the fleet stayed in port was 10% higher than in the adjacent weeks.

There remains a need to quantitatively understand the nature of the effect of vessel interactions. In this paper, we focus on vessel interference effects, where interference is ecologically defined as a rapidly reversible depression in foraging (catch) rate (CPUE) with increasing foraging (fisher, or vessel) density (Rijnsdorp et al., 2000b). While the hypothesised effect of vessel interference is most pronounced around sudden and large reductions in effort, as per a buyback scheme, smaller-scale interference is presumably occurring in an ongoing manner. In the context of CPUE time series continuity, it is important to identify and isolate the effect of changes in the effort (i.e. number of vessels) on the CPUE. Awareness of technical interactions is common, yet it has not been described in the context of rapid changes of effort brought about by management interventions such as the structural adjustment; we attempt to provide a simple quantitative description of the processes involved.

While interference is commonly acknowledged, there are few empirical studies quantifying vessel interference. Those examples are largely centred on the assumption of an ideal free distribution (Fretwell and Lucas, 1970). Gillis et al. (1993) noted that many traditional analyses of fisheries data assume that i) there is a negligible effect of alternative fish stocks on the spatial distribution of fishing effort (the "dynamic pool assumption"), and ii) the localisation of effort does not influence catchability. Such assumptions can lead to potential biases in the interpretation of CPUE statistics. Assuming an ideal free distribution, Gillis et al. (1993) found evidence for competition among vessels, but its mechanism, whether interference or exploitation competition, was unable to be determined.

Gillis and Peterman (1998) examined the relationship between catch rate and abundance incorporating a vessel interference term as an input parameter to a model based on the assumption of an ideal free distribution (see also Gillis, 2003). They used Hassel and Varley’s (1969) form of interference among foraging insects to define fishing mortality, \( F(E) \) as a function of catchability, \( q \), effort, \( E \), and a vessel interference term, \( m < 1 \): \[ F(E) = qE^{1-m} \]

Results indicated that even low levels of interference among fishing vessels can cause a breakdown in the correlation between CPUE and local abundance.

Gillis and van der Lee (2012) developed theoretical curves of equal catch rates, to test ideal free distribution hypotheses, and suggested that non-linear effects may arise from extreme interference competition.

Poos and Rijnsdorp (2007) estimated the strength of interference competition by considering the decline in value-per-unit-effort about a sudden increase in vessel density associated with a local area closure. They argued that because interference acts immediately, and exploitation acts gradually, interference and exploitation competition can be disentangled if a sudden change in vessel density occurs. We employ the same logic but in a theoretical context.

Structural adjustments such as vessel buybacks do not occur frequently in fisheries, but have major economic and sustainability impacts when they do (Vieira et al., 2010). In this paper, we explore the hypothesis that the dramatic observed changes in the CPUE for some species are due to vessel interactions (interference between vessels) that the current statistical CPUE standardisation does not take into account. Our theoretical approach extends the simple Schaefer model such that catch rate is an inverse function of the number of vessels, with the latter weighted by a parameter, \( \beta \), describing the magnitude of the effect of vessel numbers. We derive an equation for \( \beta \) based on two main assumptions pertaining to biomass, and investigate the extent to which our solution holds under alternative conditions. This is the first attempt to provide an independent means of directly quantifying a vessel interaction effect that is process-based rather than fitted to data.

2. Methods

We work with a discrete time Schaefer model for population size \( N(t) \) at time \( t \):

\[ N(t + 1) = N(t) + rN(t) \left( 1 - \frac{N(t)}{K} \right) - C(t) \]  

where

\[ C(t) = \frac{QV}{1 + \beta V} N(t) \]  

with the usual interpretations of \( r \) as the maximum per capita reproduction, \( K \) as the carrying capacity of the population and \( Q \) as the catchability. \( V \) is the number of vessels (equating to an effort measure), and \( \beta \) is a coefficient reflecting the magnitude of the effect of vessel interference on catchability. We here treat catchability independently from the effects of interference. However, since interference, as modelled here, clearly impacts the proportion of the exploitable stock biomass taken with one unit of effort, per the classic definition of catchability, \( q \), (Haddon, 2011), we replace the classic \( q \) by \( Q \), which represents the classic catchability, \( q \), when \( \beta \) is zero. Alternatively, \( \frac{Q}{1 + \beta V} \) equates to the classic catchability \( q \) when \( V = 1 \). Thus the term \( \frac{QV}{1 + \beta V} \) is essentially the traditional catch equation \( C = qEN \), where \( E \) equates to effort and the term \( \frac{1}{1 + \beta V} \) captures the effect of vessel interference. We are assuming interference competition not exploitation competition (sensu Poos and Rijnsdorp (2007)), and, for simplicity, we assume that \( r, K, \) and \( Q \) are known.

Our use of an asymptotic relationship to represent interference differs from Gillis and Peterman’s (1998) power relationship. The latter has fishing mortality increasing exponentially when the vessel interference term is less than \( 0 \), where fishing mortality at zero interference is a point on the continuum. In contrast, equation (1a) imposes an asymptote about zero interference, meaning that fishing mortality is maximised in the absence of interference.
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