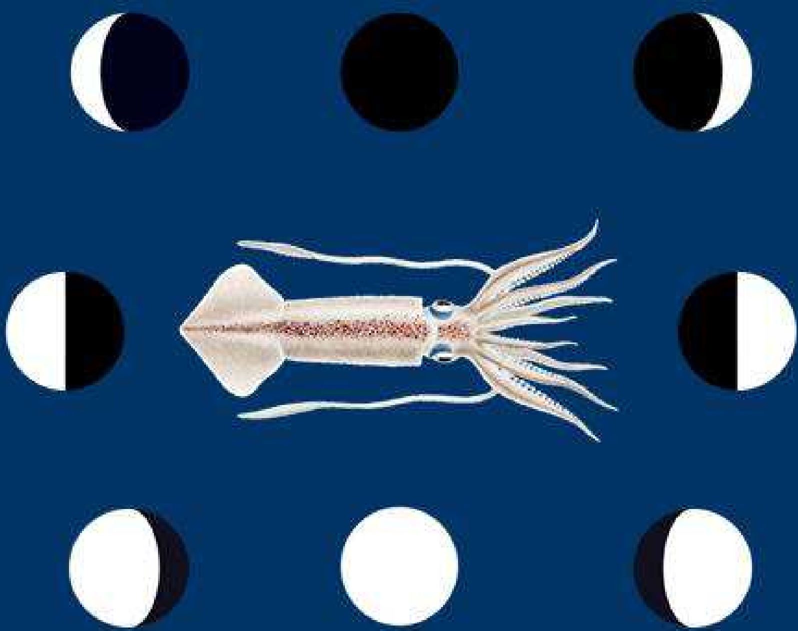
Lunar phase influence on *Doryteuthis gahi* trawl catches.



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Summary

The relationship was studied between lunar phases and catches in the *Doryteuthis gahi* trawl fishery. Catches were standardized from summer seasons and winter seasons, 2009 to 2020, and modelled against the proportion of the lunar cycle on each day. Lunar cycle proportions were statistically significant but explained very little of the variation in daily catches. Average catches after full moons were significantly lower than before full moons, while average catches before and after new moons were not significantly different, indicating that the primary lunar influence was through changes in illumination, not tidal flow.

Introduction

The Falkland Islands trawl fishery for *Doryteuthis gahi* squid (Loliginidae) is managed by limiting stock depletion to a conservation threshold of 10,000 tonnes biomass (Barton 2002). Commercial fishing seasons are scheduled to coincide with the ontogenetic out-migration of *D. gahi* to their feeding grounds on the shelf (Hatfield and des Clers 1998), but in most years pulses of out-migration continue to occur iteratively during the season (Roa-Ureta 2012, Winter and Arkhipkin 2015). The management decision to close a fishing season against the conservation threshold then depends not only on calculating the stock biomass present, but also on anticipating the likelihood of further migration pulses.

Studies have found that the migration pulses of *D. gahi* are influenced by oceanographic currents (Arkhipkin et al. 2004, Arkhipkin et al. 2006), and by wind vectors (Winter and Arkhipkin 2015). However, an influence on *D. gahi* that has not been studied yet is the lunar cycle. The potential for a lunar effect is suggested by observations of other marine animals that respond to heightened tidal flows, including mullet *Liza aurata* and *L. saliens* (Katselis et al. 2007), grunion *Leuresthes tenuis* (Martin and Raim 2014), ocypodid and grapsid crab larvae (Skov et al. 2005), or to changes in luminosity including sole *Solea senegalensis* (Vinagre et al. 2006), seabream *Sparus aurata* (Katselis et al. 2007), zooplankton (Hernández-León et al. 2002), and euphausiids *Meganyctiphanes norvegica* (Tarling et al. 1999). In turn, predatory squid such as *Dosidicus gigas* have been found to target prey at depths that may be influenced by the lunar phase (Gilly et al. 2006).

D. gahi are predatory (Guerra et al. 1991), and migrate vertically (Winter et al. 2013) as well as ontogenetic horizontally (Arkhipkin et al. 2004). Lunar cycles could affect behaviour and movement of *D. gahi* directly or indirectly. This study examined the relationship between commercial daily trawl catches of *D. gahi* in the Falkland Islands and the corresponding lunation. The hypotheses are tested that new moons and full moons particularly influence the catchability of *D. gahi*.

Methods

D. gahi in the Falkland Islands are fished in two seasons per year; in austral summer (February to April) and austral winter (July to September) (Arkhipkin et al. 2013). In either season vessels report daily catch totals to the Falkland Islands Fisheries Department. For this analysis, data from summer seasons 2009 – 2020 and winter seasons 2009 – 2019 were included; 23 seasons in total. Season data were aggregated separately by the summer and winter fisheries, as summer and winter seasons target different cohorts of the squid (Arkhipkin et al. 2013) and are subject to different daylight regimes. Vessels generally aim to catch as much as they can process in 24 hours; therefore catches per day can be considered a catch-per-unit-effort.

D. gahi catches per day were standardized by dividing each catch by its season's maximum catch, to avoid aggregates of summer and winter seasons being skewed by differences among years in absolute biomass of the *D. gahi* stock available to the fishery. Each season's maximum catch was checked by the Grubbs test for outliers (Grubbs and Beck 1972; implemented in R code, Komsta 2015), so that the actual divisor was the maximum catch not identified as an outlier at $p < 0.05$.

For time periods corresponding to the fishing seasons, measures of percent moon visibility per night were taken from the website www.calendar-365.com/moon-calendar/. To mitigate aberrations, percent visibility entries per day from the website were LOESS-smoothed with a span equivalent to (N season-days)$^{-1}$/12 (approximately a factor of 1/9), and expressed as a proportion of the lunar cycle where new moon (0% visibility) = 0/1 of the lunar cycle, and full moon (100% visibility) = 0.5 of the lunar cycle.

Daily standardized *D. gahi* catches in the summer and winter fisheries were modelled on lunar cycle proportions using generalized additive models (GAM), which require no prior assumption of the number of response variable modes in a cycle. To avoid edge effects of the highest and lowest lunar cycle proportions, either summer or winter data set was replicated end-to-end 3× with –1, 0, and +1 added to the lunar cycle proportions of the first, second, and third replicates, the GAM calculated across all replicates, and the middle (0) replicate retained. For comparison, the mean lunar phase as a composite vector (mean direction) and circular variance ($0 \leq V_m \leq 1$) were also calculated (Cremers and Klugkist 2018).

Permutation tests were run to evaluate the significance of difference in catches shortly before and after new moon and full moon; the lunar phases that cause highest tidal ranges (Webb 2019). If *D. gahi* catches correlate with the lunar cycle because squid are carried into the fishing zone on higher tidal flows, then catches following maximum tides (spring tides) should be higher than before maximum tides. But if *D. gahi* catches correlate with the lunar cycle because squid respond to changes in light, then catchability before and after maximum tides should not be substantially different, as waxing and waning moons are equally luminous. Alternatively, catches may decline over time anyway as the ongoing fishery depletes the stock. To run the tests, catches per vessel per season were randomly permuted relative to the day (and lunar cycle proportion) on which they were taken. Permutations were iterated 30,000×. At each iteration, the averages of all catches from all vessels and seasons were recomputed within 0.05 before and after the new moon (0.95 – 0.00 vs. 0.00 – 0.05 of the lunar cycle) and before and after the full moon (0.45 – 0.50 vs. 0.50 – 0.55 of the lunar cycle). Two-tailed significance was calculated as the proportional numbers of permutations with absolute average catch differences before/after ≥ than the observed absolute average catch differences.

Results

Summer seasons

A total of 10,640 daily catch reports were recorded from twelve summer seasons. One of these twelve seasons (2015) had been closed early by emergency order; anticipating that stock biomass would fall below the conservation threshold of 10,000 tonnes. The summer season GAM of daily standardized *D. gahi* catches vs. lunar cycle proportions was highly significant ($p < 0.001$), with maximum of 0.398 standardized catch at 0.820 of the lunar cycle and minimum of 0.380 standardized catch at 0.300 of the lunar cycle (Figure 1). However, the GAM explained little of the deviance ratio: $R^2 = 0.0014$. Correspondingly, the mean lunar phase was 0.771 with a high circular variance of 0.995.

Standardized catches within 0.05 before the new moon (N = 620) averaged 0.375; standardized catches within 0.05 after the new moon (N = 1506) averaged 0.392. The difference of +0.017 was marginally significant at $p = 0.075$ by the permutation test. Standardized catches within 0.05 before the full moon (N = 983) averaged 0.405; standardized catches within 0.05 after the full moon (N = 1148) averaged 0.371. The difference of –0.034 was significant at $p < 0.001$.

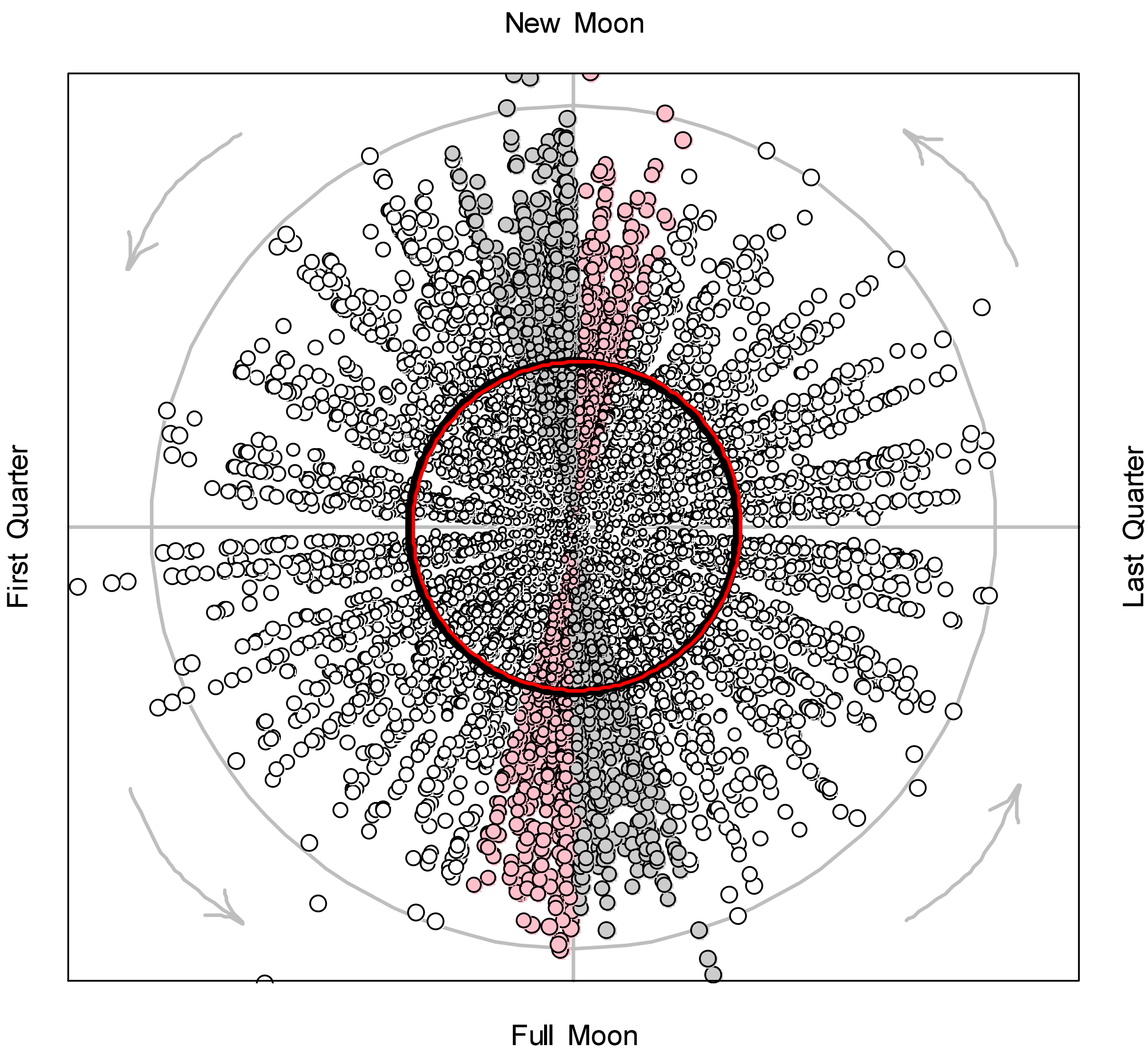

Figure 1. Distribution of standardized daily catches (N = 10,640) in summer seasons 2009 – 2020 relative to the lunar cycle. Grey circle perimeter: standardized catch = 1. Pink symbols: standardized catches within 0.05 of the lunar cycle before new and full moons. Grey symbols: standardized catches within 0.05 of the lunar cycle after new and full moons. Red line: GAM prediction of standardized catch per lunar phase. For clarity, the GAM prediction is superimposed on a true circle (in black) the width of its minimum to maximum.

Winter seasons

A total of 10,863 daily catch reports were recorded from 11 winter seasons; four of which had been closed early by emergency order (2009, 2011, 2015, and 2019). The winter season GAM of daily standardized *D. gahi* catches vs. lunar cycle proportions was also highly significant ($p < 0.001$), but with only slightly more deviance explained than for summer seasons: $R^2 = 0.0096$. GAM prediction obtained a maximum of 0.359 standardized catch at 0.025 of the lunar cycle, and a minimum of 0.310 standardized catch at 0.505 of the lunar cycle (Figure 2). The mean lunar phase was 0.054 with a circular variance of 0.994.

Standardized catches within 0.05 before the new moon (N = 737) averaged 0.347; standardized catches within 0.05 after the new moon (N = 1370) averaged 0.359. The difference of +0.012 was not significant at $p > 0.150$. Standardized catches within 0.05 before the full moon (N = 1148) averaged 0.326; standardized catches within 0.05 after the full moon (N = 1170) averaged 0.300. The difference of –0.025 was significant at $p < 0.002$.

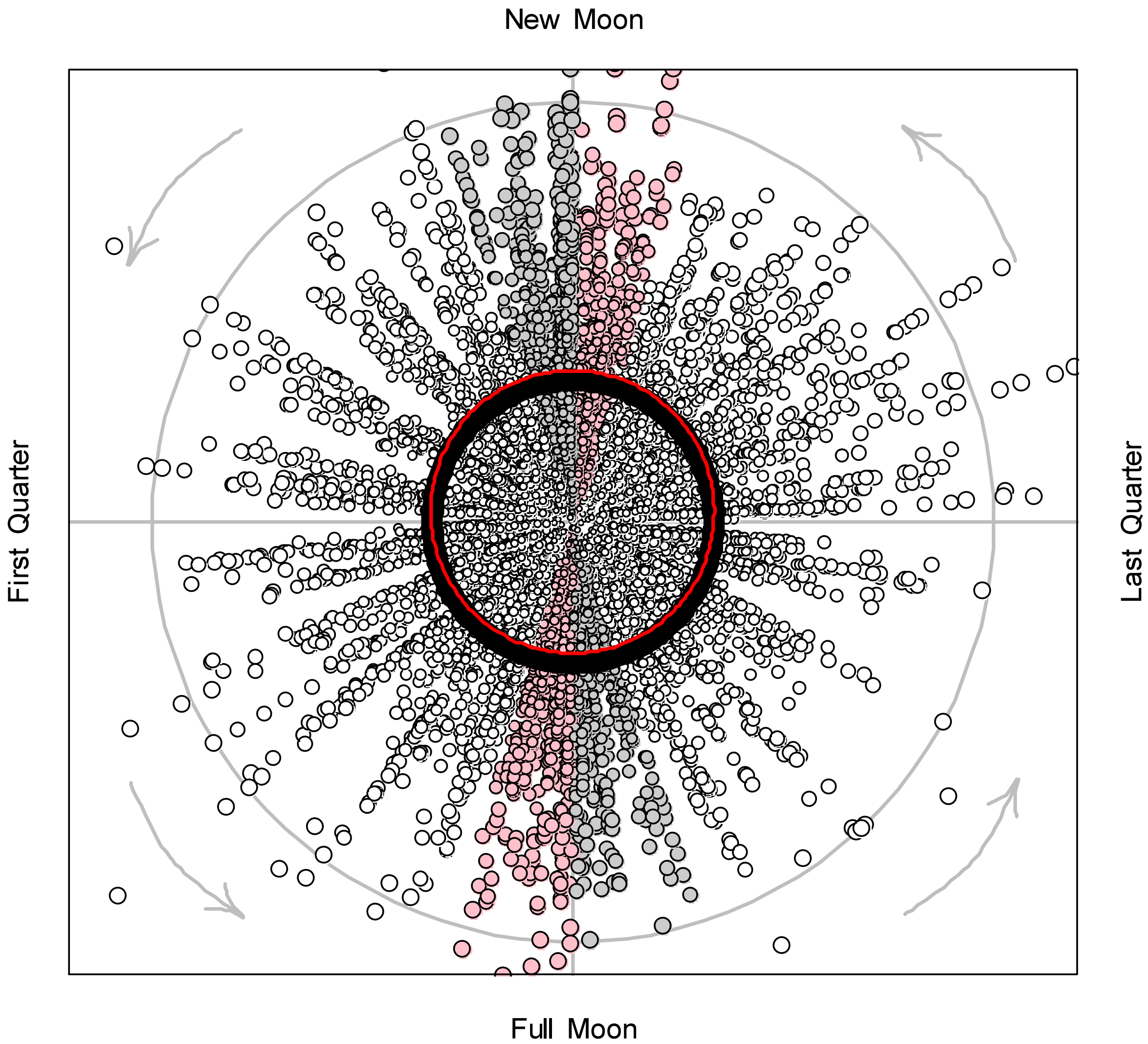

Figure 2. Distribution of standardized daily catches (N = 10,863) in winter seasons 2009 – 2019 relative to the lunar cycle. Plot description as Figure 1.

Conclusions

Average catch differences of *D. gahi*, before and after new and full moons, gave evidence that the predominant lunar phase influence on this fishery was through luminosity rather than tidal flow. Average catches in both seasons were significantly lower after full moons, but not significantly different after new moons. The outcome appeared to be the same whether the cyclical maximum of *D. gahi* catch coincided closely with new moons, as in winter, or showed no relation to either new moon or full moon phases, as in summer.

Quantitatively, lunar phase influences were low despite high statistical significance. Phototaxis has been observed in loliginid squid (Hanlon et al. 1980, Martins and Perez 2006), but this behaviour may have only a minor effect in fisheries using mobile near-bottom trawl gear. In contrast, the lunar cycle was found to be a major influence in jig and trap-net squid fisheries, which require the animals' own movement to encounter the fishing gear (Yamashita and Matsushita 2013, Masuda et al. 2014). Lunar phase effects may further be dampened in an industrial fishery where vessels work day after day, compared to game fisheries (Ortega-Garcia et al. 2008) or artisanal fisheries (Postuma and Gasalla 2010, Bos and Gumanao 2012) where vessels can more facultatively choose favourable moon periods.

D. gahi is one of the primary fishery resources of the Falkland Islands Shelf (Arkhipkin et al. 2008), and like species in all marine systems, responds to a range of signals. The lunar phase appears to be an extant, but overall not major factor in migration pulses of *D. gahi*, as measured from commercial catches. Squid populations are highly variable, however, and future changes in environmental conditions may bring about differing interactions.

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