Throwing light on straddling stocks of Illex argentinus: assessing fishing intensity with satellite imagery

C.M. Waluda, P.N. Trathan, C.D. Elvidge, V.R. Hobson, and P.G. Rodhouse

Abstract: Marine fisheries provide around 20% of animal protein consumed by man worldwide, but ineffective management can lead to commercial extinction of exploited stocks. Fisheries that overlap nationally controlled and high seas waters cause particular problems, as few management data are available for the high seas. The Argentinean short-finned squid, *Illex argentinus*, exemplifies such a “straddling stock”. Here we demonstrate that light emitted by fishing vessels to attract squid can be detected via remote-sensing. Unlike conventional fisheries data, which are restricted by political boundaries, satellite imagery can provide a synoptic view of fishing activity in both regulated and unregulated areas. By using known levels of fishing effort in Falkland Islands waters to calibrate the images, we are able to estimate effort levels on the high seas, providing a more comprehensive analysis of the overall impact of fishing on the stock. This innovative tool for quantifying fishing activity across management boundaries has wide-ranging applications to squid fisheries worldwide.

Introduction

A “straddling stock” of a species of squid, or other living marine resource, is one that is harvested in both nationally controlled (exclusive economic zone; EEZ) and high-seas (international) waters. EEZs typically extend up to 200 miles from the coastline of a country, whereas the “high seas” incorporate the open ocean outside EEZ regions (Doulman 1995). Within an EEZ, fishing is usually regulated and managed by the relevant authorities, whereas on the high seas, fishing is generally unregulated. Fisheries data, on the number and size of vessels, catch rate, and effort spent fishing, are usually available for EEZ waters, but rarely for the high seas. Straddling stocks inhabit both areas, so the overall fishing impact on a stock is uncertain, potentially undermining long-term sustainable management methods for a fishery.

The winter spawning stock of *Illex argentinus* in the Southwest Atlantic is an important example of a highly mi-
gratory straddling stock. This stock is fished on the southern Patagonian shelf, south of 42°S (Haimovici et al. 1998). This is one of the widest shelf areas in the world, extending up to 500 miles from the coast of South America (Longhurst 1998). Here the stock straddles both the high seas and two nationally controlled areas: the Falkland Islands Conservation Zone (comprising the interim conservation and management zone (FICZ) and outer conservation zone (FOCZ); extending 150 and 200 miles from the coast, respectively), and the Argentinean EEZ (extending 200 miles from the coast).

In common with the majority of commercially exploited squid species, I. argentinus has a life span of one year, so the fishery exploits a new year-class at the start of each fishing season. Management of the stock in the Falkland Islands fishery is based on allowing sufficient numbers of squid to escape at the end of the fishing season to propagate the next generation, which then becomes the sole target of the fishery in the following year (Rosenberg et al. 1990). Fishing in Falkland Islands and Argentinean waters has been licensed since 1987 and 1993, respectively (Rosenberg et al. 1990; FIGFD 1997). Despite the strict regulations in place in these areas, squid must pass through unregulated high seas waters on their return migration to the spawning grounds. This may have significant consequences for stock conservation, as it exploits some of the squid that fishery management has allowed to escape for spawning.

As with most major squid fisheries targeting the family ommastrephidae (i.e., "short-finned" squid), I. argentinus is predominantly caught by jigger vessels, which fish at night. These operate using jigs—coloured lures armed with a crown of barbless hooks. A typical vessel deploys at least 2500 jigs simultaneously and may catch more than 30 tonnes of squid in one night (Rodhouse et al. 2001). To attract squid to the jigs, powerful incandescent lamps are used. These are usually 2 kW each and a typical vessel uses up to 300 kW for light production (Rodhouse et al. 2001). The emission of light from squid fishing vessels is detectable throughout the worlds oceans using imagery from the United States Air Force Defence Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) (Rodhouse et al. 2001). This paper presents the first application of DMSP-OLS imagery, coupled with geographical information system (GIS) techniques to observe and quantify fishing activity throughout the whole of the Southwest Atlantic squid fishery, including the high seas area. We test the hypothesis that light emitted by vessels in Falkland Islands waters can be used to estimate the number of vessels fishing, and thus used to calculate the number of vessels fishing in high seas waters. This potentially provides a tool to better account for fishing across the range of the species distribution, which could improve estimates of the total catch of I. argentinus, and aid in stock management.

Materials and methods

Fishery description

A series of 15 single-pass visible-band images were obtained from the DMSP-OLS for the region shown in Fig. 1. Images (with a maximum pixel resolution of 2.7 km, or 0.008°) were selected for the period January–June 1999, corresponding to the period during which the Falkland Islands I. argentinus fishery was operational. All satellite passes were made between the hours of 2300 and 0100 local time. Each image was georeferenced and cloud-cleared using algorithms developed by the National Geophysical Data Center (NGDC, Boulder, Colo. (Elvidge et al. 1999)). Using a GIS, images were overlaid with spatial data comprising the 200-m bathymetric contour and the boundaries of the Falkland Islands, high seas, and Argentinean fishery zones (see Fig. 1). The selected images were examined visually to describe the distribution of the fleet throughout the season, to relate fleet distribution to the known distribution and lifecycle of I. argentinus.

Calibration and estimation of vessel numbers

Data on fishing effort in Falkland Islands waters was obtained from the Falkland Islands Government Fisheries Department (FIGFD). Effort was measured as the number of vessels fishing in Falkland Islands waters for the night corresponding to each image. The number of illuminated pixels in the Falkland Islands and high seas regions were obtained from each image, using algorithms developed by the NGDC (Elvidge et al. 1999). Using fishery data from Falkland Islands waters and data on the number of illuminated pixels in this region, a regression equation relating the number of pixels and the number of vessels was derived (Fig. 2a). Using this calibration, the number of vessels fishing in high seas waters were estimated based on the number of illuminated pixels recorded in the high seas area. Additionally, the number of vessels fishing in Falkland Islands waters was calculated using the regression equation (Fig. 2a) to test the reliability of using the method.

Results

Fishery description

We provide a chronological series of satellite images from the 1999 fishing season in the Southwest Atlantic (Fig. 1). In January, fishing lights are observed towards the north of the region, specifically on the high seas at around 46°S (Fig. 1). In February, the fleet spreads southward along the shelf-break, moving into the Argentinean EEZ and the western part of the Falkland Islands Conservation Zone. In early April, fishing concentrations form to the north of the Falkland Islands and close to the shelf-break in all three regions. The fleet reaches the southwesterly point of its distribution (around 52°S, 61°W) by 24 April. Fishing continues to occur in Falkland Islands waters and along the shelf-break until early June, when the fleet disperses and moves northwest into the Argentinean EEZ and the high seas. By 17 June the Falkland Islands fishery is closed, whereas vessels continue to operate in Argentinean and high seas waters north of 48°S. Of particular note is that portion of the shelf-edge that lies in the high seas area (between 45°S and 47°S), which supports substantial fishing activity throughout the season, as evidenced by the presence of fishing lights in each of the images shown (Fig. 1).

Calibration and estimation of vessel numbers

In Falkland Islands waters, the number of vessels operating in 1999 (over the period of the images presented in Fig. 1) ranged between 48 and 86 vessels (mean = 75 ± 13,
Using the calibration given in Fig. 2a to indicate fishing intensity in terms of number of vessels fishing, we estimate that from January to June 1999 between 61 and 82 vessels (mean = 58 ± 6, SD) were operating in the high seas fishery (Fig. 2b). The estimated number of vessels present on the high seas varied throughout the season, and was less consistent than in Falkland Islands waters. During the 1999 season, the estimated number of vessels fishing on the high seas was usually lower than or equivalent to that in Falklands waters (Fig. 2b). However, after the close of the Falkland Islands fishery (15 June 1999), when a proportion of the surviving squid were migrating north along the shelf-edge to the spawning grounds, significant fishing continued on the high seas (an estimated 69 vessels on 17 June 1999; Figs. 1 and 2). Estimation of fishing in Falkland Islands waters suggested that between 61 and 95 vessels were fishing (mean = 75 ± 9, SD) during the period of the study (Fig. 2b). This suggests a discrepancy of between 2 and 15 vessels with a mean of 8 (i.e., within ±11%) between the observed and actual number of vessels fishing.

**Discussion**

Satellite images obtained from DMSP-OLS can be success-
Fig. 2. (a) The number of vessels fishing in Falkland Islands waters versus the number of illuminated pixels in corresponding Defence Meteorological Satellite Program (DMSP) images. Dates as in Fig. 1. (—) Regression line ($R^2 = 0.51$); (— - -) 95% confidence intervals. (Regression equation: $N_{vessel} = 55.3 + 0.0101 \times N_{pixels}; n = 13; F_{[1,12]} = 11.4; P = 0.006$). (b) Number of fishing vessels in Falkland Islands waters (observed and estimated) and high-seas waters (estimated), Southwest Atlantic. Dates are given as days from 1 January 1999, corresponding to images in Fig. 1. Observed Falkland Islands data (closed circles, solid lines) obtained from Falkland Islands Government Fisheries Department. Estimated data from: the high seas (open circles, solid lines) obtained from Falkland Islands Government Fisheries Department. Estimated data from: the high seas (open circles, dashed line) and the Falkland Islands (triangles, dashed-dotted line) calculated using the regression equation given above.

![Graph](image)

fully used to observe the distribution of the fleet throughout the fishing season, and it is possible to interpret the fleet distribution in light of the known life cycle of *I. argentinus*. In the austral winter, before the fishing season begins, squid eggs hatch over the northern Patagonian shelf (Haimovici et al. 1998). During late winter, newly hatched “paralarval” squid are most commonly found off the Rio de la Plata in latitudes of 32°S to 39°S (Brunetti and Ivanovic 1992; Haimovici et al. 1998). Early in the season (January–March), the fishery follows feeding migrations of squid travelling south from the nursery areas of the northern Patagonian shelf (Haimovici et al. 1998). This can be clearly seen in the southerly progress of fishing lights along the shelf-edge, with the location of fishing vessels closely tracking the shelf-break (200-m bathymetric contour).

The largest catches are made mid-season (April–May) when the fishery targets feeding aggregations of squid over the southern Patagonian shelf, particularly near the Falkland Islands (Rodhouse et al. 1995). Late in the season (June), the fleet moves northwards, following squid as they leave Falkland Islands waters on their return migration to the northern Patagonian shelf. Here, squid spawn and die, completing their one-year life cycle (Rodhouse et al. 1995; Haimovici et al. 1998). It is clear that the distribution of the fleet closely tracks the adult phase of the annual migratory cycle. We have shown that the high seas region supports substantial fishing throughout the season, which has significant consequences for the management of the stock as a whole.

The management of the Falkland Islands fishery has been arguably among the most successful in the world (Pierce and Guerra 1994). However, despite the strict regulations in Falkland Island (and Argentinean) waters, *I. argentinus* must pass through unregulated high seas fishing areas during their northerly migration. Total escapement levels set by management authorities does include an element associated with unregulated fishing during migration (D.J. Agnew, Renewable Resources Assessment Group, Imperial College, London, U.K. personal communication), and the use of DMSP-OLS imagery potentially provides a tool for enhancing management procedures to better account for the exploitation of the stock in the high seas region. The use of a linear regression model provides a simple method that has been shown to estimate the number of vessels fishing in the Falkland Islands region to within around 11% of the actual number of vessels. Extrapolating this to the high seas suggests that the estimates of fishing are likely to be reasonable, and useful during those periods where data on high seas fishing are not available.

The regression equation indicates that there was a “background level” of around 55 vessels. This may relate to the range of data used and the fact that the regression may not be linear. In addition, it is not always possible to view individual vessels, as the light signatures of vessels fishing closely together tend to merge into one continuous lit area. This may result in an underestimate of the numbers of vessels fishing. To address this problem, further work will focus on improving the calibration between lit pixel and vessel numbers by using high-resolution data on specific vessel locations. In addition, the inclusion of additional satellite images, and more rigorous statistical analyses are required to provide a more precise estimate of high seas fishing and to further account for noise caused by factors such as high cloud, glare, and atmospheric scintillation.

The work presented here demonstrates an innovative method for estimating the number of vessels fishing on a highly migratory squid stock that straddles several political regions. This technique is transferable to other squid fisheries that operate using lights, for example, in the Sea of Japan, the South China Sea, the Gulf of Thailand, and the eastern Pacific (Rodhouse et al. 2001). In terms of global productivity, squid fisheries are becoming increasingly important, particularly with the decline in catches from many traditional finfisheries (Caddy and Rodhouse 1998).
Using satellite imagery to monitor the exploitation of straddling stocks across their entire distributional range has the potential to contribute to the sustainable management of stocks, and hence maintain the wider ecosystem structure. *Illex argentinus* is an important link in the food web of the southern Patagonian shelf as both a predator and a prey species (Haimovici et al. 1998). The Patagonian shelf-edge is an important feeding area for many higher predators, such as elephant seals, albatrosses, and petrels (see, e.g., Grémillet et al. 2000). These species forage in the shelf-break region and are dependent on the sustainable management of the ecosystem. Proper management of *I. argentinus* is therefore critical not only for sustainable exploitation, but also for maintaining ecological balance.

**Acknowledgements**

Support from the British Antarctic Survey (Natural Environmental Research Council) is gratefully acknowledged. We would like to thank J. Barton, Falkland Islands Fisheries Department, for supplying the fishery data, and for helpful comments on the manuscript. We thank D.J. Agnew, Renewable Resources Assessment Group (RRAG), Imperial College, for valuable discussions and input to this research, and L.S. Peck and A.L. George for useful comments on an earlier draft. This research forms part of an Independent Project awarded to P.G.R. and funded under the British Antarctic Survey’s Antarctic Science in the Global Context Programme.

**References**


