Progress in Oceanography 128 (2014) 60–73

Contents lists available at ScienceDirect

Progress in Oceanography

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

Ecosystem scenarios shape fishermen spatial behavior. The case of the Peruvian anchovy fishery in the Northern Humboldt Current System

Rocio Joo [a,b,*], Arnaud Bertrand [a], Marilu Bouchon [b], Alexis Chaigneau [c], Hervé Demarcq [a], Jorge Tam [b], Monique Simier [a], Dimitri Gutiérrez [b], Mariano Gutiérrez [d], Marceliano Segura [b], Ronan Fablet [e], Sophie Bertrand [a]

[a] Institut de Recherche pour le Développement (IRD), Centre de Recherche Halieutique Méditerranéenne et Tropicale, Avenue Jean Monnet, CS 30171, 34203 Sète Cedex, France
[b] IMARPE, Esquina Gamarra y General Valle S/N Chucuito, Callao, Lima, Peru
[c] Institut de Recherche pour le Développement (IRD), UMR LEGOS, CNES/CNRS/IRD/UPS, 18 Avenue Edouard Belin, 31400 Toulouse, France
[d] Facultad de Oceanografía y Pesquería, Universidad Nacional Federico Villareal, Calle Roma 350, Miraflores, Lima, Peru
[e] Institut Telecom/Telecom Bretagne, UMR 6285 LabSTICC, TOMS (Statistical Signal Processing and Remote Sensing), Technopole Brest-Iroise, CS 83818, 29238 Brest Cedex 3, France

ARTICLE INFO

Article history:
Received 23 August 2013
Received in revised form 24 July 2014
Accepted 14 August 2014
Available online 27 August 2014

ABSTRACT

A major goal in marine ecology is the understanding of the interactions between the dynamics of the different ecosystem components, from physics to top predators. While fishermen are among the main top predators at sea, almost none of the existing studies on ecology from physics to top predators contemplate fishermen as part of the system. The present work focuses on the coastal processes in the Northern Humboldt Current System, which encompasses both an intense climatic variability and the largest monospecific fishery of the world. From concomitant satellite, acoustic survey and Vessel Monitoring System data (~90,000 fishing trips) for a ten-year period (2000–2009), we quantify the associations between the dynamics of the spatial behavior of fishermen, environmental conditions and anchovy (*Engraulis ringens*) biomass and spatial distribution. Using multivariate statistical analyses we show that environmental and anchovy conditions do significantly shape fishermen spatial behavior and present evidences that environmental fluctuations smoothed out along trophic levels. We propose a retrospective analysis of the study period in the light of the ecosystem scenarios evidenced and we finally discuss the potential use of fishermen spatial behavior as ecosystem indicator.

Introduction

Marine ecosystems are highly structured in space (Margalef, 1979) and pelagic ecosystems, where habitats are made of constantly moving water masses, are also highly dynamic in time (Levin, 1992; Fréon and Misund, 1999). Because those natural systems tend to be out of balance (Pimm, 1991), it is fundamental to consider their spatio-temporal variability to understand the relative contributions of bottom-up and top-down controls in their functioning (Matson and Hunter, 1992; Gripenberg and Roslin, 2007; Polishchuk et al., 2013). Also, in general, since each organism tends to feed on smaller organisms, the high-frequency environmental variations tend to smooth out along trophic levels (Mann and Lazier, 2006).

Observation limitations to examine such processes have been largely overcome in the last decades thanks to new technologies and ecosystem models. There are now, in several ecosystems, spatially explicit data on abiotic factors, prey and predator distribution and abundance at high time resolution (Costa, 1993; Decker and O'Dor, 2003; Boyd et al., 2004; Rutz and Hays, 2009; Bograd et al., 2010). Recent works studied the linkages between environmental conditions, prey distribution and predators' behavior in time and space. The predators studied included sea mammals (Croll et al., 2005; Stevick et al., 2008; Cotté and Guinet, 2011; Hazen et al., 2011; Santora et al., 2012; Thompson et al., 2012), seabirds (Embling et al., 2012; Santora et al., 2012; Thompson et al., 2012) and fish (Thompson et al., 2012; Embling et al., 2013).

---

* Corresponding author. Address: Instituto del Mar del Peru (IMARPE), Esquina Gamarra y General Valle S/N Chucuito, Callao, Lima, Peru. Tel./fax: +51 (1) 441 32 23; fax: +51 (1) 441 32 23.

E-mail addresses: rocio.joo@gmail.com (R. Joo), Arnaud.Bertrand@ird.fr (A. Bertrand), mbouchon@imarpe.gob.pe (M. Bouchon), alexis.chaigneau@ird.fr (A. Chaigneau), herve.demarcq@ird.fr (H. Demarcq), jtam@imarpe.gob.pe (J. Tam), Monique.Simier@ird.fr (M. Simier), dgutierrez@imarpe.pe (D. Gutiérrez), Mariano-G@unops.org (M. Gutiérrez), msegura@imarpe.gob.pe (M. Segura), ronan.fablet@telecom-bretagne.eu (R. Fablet), Sophie.Bertrand@ird.fr (S. Bertrand).

http://dx.doi.org/10.1016/j.pocean.2014.08.009
0079-6611/

Those studies identified critical processes and key areas that can be directly useful in conservation, marine spatial planning, or in the management of human activities in marine ecosystems. Nevertheless, while fishing represents world catches of ~89.8 million of tonnes per year (between 2006 and 2011; FAO, 2012) and competes directly with natural predators, none of those studies on spatial ecology from physics to top predators contemplated fishermen as part of the system. Admittedly, fishermen are peculiar top predators because they rely on technology and are driven by a distinct currency than that of natural predators. Nonetheless, in pelagic ecosystems water masses and fish schools are constantly moving (Swartzman et al., 2008; Peraltilla and Bertrand, 2014). Thus, fishermen do face the same uncertainty on prey localization as natural predators do and their spatial behavior reflects their need for solving the same challenge. In that sense, it has been shown that fishermen in the Peruvian anchovy fishery deploy similar spatial foraging strategies to those of other animal predators (Bertrand et al., 2007).

The Northern Humboldt Current System (NHCS) off Peru provides a great opportunity for studying the association between the dynamics of ecosystem components in a bottom-up-controlled exploited ecosystem (Ayón et al., 2008; Bertrand et al., 2008a). The NHCS is characterized by an intense variability from secular to intra-seasonal timescales. Variations of the Eastern Pacific intertropical convergence zone or the Pacific decadal oscillation can impact the NHCS at inter-decadal and secular scales (Chavez et al., 2003; Gutiérrez et al., 2009; Salvatecci et al., 2012). At inter-annual scales, El Niño Southern Oscillation – characterized by relatively warm/cold El Niño/La Niña events – has a strong effect on the eastern south Pacific region (Colas et al., 2008; Takahashi et al., 2011; Dewitte et al., 2012; among others). At seasonal and intra-seasonal scales, the NHCS is mostly modulated by wave dynamics of equatorial origin and local wind forcing (Penven et al., 2005; Echevin et al., 2011, 2014; Dewitte et al., 2012; Chaigneau et al., 2013; Pietri et al., 2014). The resulting environmental scenarios directly determine the extent of the tridimensional anchovy habitat (Bertrand et al., 2004a, 2011), which in turn conditions fish availability for the main predators in this system, the fishermen (Bertrand et al., 2008a). Besides, the NHCS produces more fish per unit area than any other region in the world oceans and sustains the world's largest monospecific fishery (Peruvian anchovy or anchoveta, *Engraulis ringens*). To cope with the intense climatic variability, the management of the anchovy fishery is adaptive, i.e. catch limits are re-assessed every ~6 months and opening and closure periods decided on the basis of daily monitoring of the ecosystem, the fish population and the fishery (Chavez et al., 2008). The Peruvian Marine Research Institute (IMARPE) is in charge of this intense monitoring. It comprises satellite information on environmental conditions (e.g. sea surface temperature, chlorophyll-a and sea level anomaly, among others) at daily and weekly resolutions. Fish population distribution and biomass are monitored through scientific acoustic surveys (two to three times a year). The fishing activity is supervised through landing statistics, Vessel Monitoring System (VMS) and on-board observers reports (Bertrand et al., 2008b; Joo et al., 2011). The amount of available data makes the NHCS a highly appealing ecosystem for an integrated approach on ecosystem dynamics. In this highly-variable and data-rich ecosystem, Bertrand et al. (2008a) analyzed how large-scale oceanic forcing, via Kelvin waves, affected the coastal ecosystem (from oceanography to fishermen). They pioneered the incorporation of fishermen as a top predator for studying ecological dynamics and proposed contrasting scenarios of coastal oceanography, anchovy distribution and fishing activity, during the passage of coastally trapped upwelling and downwelling Kelvin waves.

The present work focuses more closely on the coastal processes in the NHCS, and on the spatial response of fishermen to varying environmental and anchovy conditions. In particular, we explore and quantify the associations between the dynamics of three ecosystem compartments: environmental conditions (Environment), anchovy biomass and distribution (Anchovy) and fishermen spatial behavior (Fishermen), for a ten-year period (2000–2009). Data on Environment and Anchovy were obtained from acoustic surveys performed by IMARPE and satellite observations. Data on Fishermen were based on VMS data (~90,000 fishing trips from 2000 to 2009), processed with a state-space model so that the nature of the behavior in which fishermen are engaged is known at each position (Joo et al., 2013). The existent evidence of bottom-up forcing in the NHCS (Ayón et al., 2008; Bertrand et al., 2008a) indicates that strong Environment–Anchovy and Anchovy–Fishermen associations should be expected. Since Fishermen have shown similar spatial foraging strategies to those of other predators (Bertrand et al., 2007), we hypothesize that – as for other predators – their spatial behavior responds to prey and environmental conditions. Then, significant Environment–Fishermen associations are expected, though not as strong as for Anchovy and Fishermen (direct prey–predator relationship). The studied decade does not encompass strong ENSO (El Niño Southern Oscillation) events. Season is thus expected to be the main scale of variability for environmental conditions. We tested for differences between two seasonal modes, summer and spring/winter, within each ecological compartment and analyzed trends separately for each seasonal mode. We eventually propose ecosystem scenarios based on the linkages evidenced between the three compartments and discuss the potential use of fishermen spatial behavior as ecosystem indicator.

Materials and methods

We focused on several time-periods from 2000 to 2009 such that concomitant data on the environment, fisheries acoustic and VMS were available. In total, 16 time-periods were available, 6 in austral summer and 10 in austral winter/spring (Table 1). Since only one value per time-period was obtained for each Anchovy descriptor, one representative value per time-period was computed for each Environment and Fishermen descriptor. This measure allowed for multivariate analyses involving the three compartments.

Environmental data

For each time-period, we produced a description of the environment as detailed in Table 2. We used sea surface temperature (SST)

Table 1
Number of fishing trips corresponding to each time-period.

Time-period	Fishing trips
2000/06–07	5839
2000/10–11	5750
2001/03–04	7012
2001/07–08	865
2001/10–11	1612
2002/02–03	1368
2002/10–11	6409
2003/10–12	6262
2004/11–12	8983
2005/11–12	15,252
2006/02–04	2990
2006/11–12	8593
2007/02–04	2395
2008/02–04	4611
2008/11–12	8604
2009/02–04	3151