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Environmental factors influencing the recruitment and catch of tropical *Panulirus* lobsters in southern Java, Indonesia

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A B S T R A C T

Tropical *Panulirus* lobster fisheries in many parts of the world are open-access and poorly-regulated. This is in part because tropical *Panulirus* lobsters have an extended pelagic larval phase (up to 9 months) and their larval settlement may take place in different habitats and depths. When recruits of a fishery are believed not spawned locally, regulatory incentives are weak. We assessed the potential sources of recruits to a small, valuable fishery for six species of *Panulirus* lobster in southern Java, Indonesia with a larval advection model. The model predicted that between 1993 and 2007, 50–90% of the recruits were sourced locally compared to a mean of 25% from remote locations. The relative intensity of the Indonesian flow-through, the south Java current and seasonal onshore winds appear to be important in the local retention of recruits. Local fisheries records showed a strong seasonality in catch that we compared to potential environmental triggers with boosted regression trees. We found that the increased catch was associated with the rapid onset of increased rainfall (> 90 mm) at the start of the monsoon (November–May). Fishers believe the coastal runoff during periods of high rainfall increases turbidity and thus enhanced catchability. Catches declined dramatically during an extended monsoon in 2010–2011, but recovered in early 2012 when rainfall patterns became more seasonal. These combined results show that there may be potential benefit of implementing local fisheries management regulations to increase sustainability. However, their effectiveness may be difficult to detect due to the strong influence of climate and oceanographic variability on both recruitment and subsequent catch.

1. Introduction

Management of tropical rock lobster (*Panulirus* species) fisheries in less developed countries is challenging. Tropical lobsters have a complex life cycle with an extended pelagic larval phase (> 6 mo: Phillips et al., 2006) and post-settlement phases that occupy different habitats and depths (Haywood and Kenyon, 2009). The long larval phase means that larvae can potentially disperse long distances from their natal reefs. During this extended larval phase, they are exposed to a range of environmental conditions that affect their survival and subsequent recruitment (Caputi et al., 2001). This makes managing fisheries of these species especially challenging when the appropriate spatial scale of management is unclear (Lipcius et al., 2001; Butler et al., 2011).

The tropical rock lobster fishery throughout Indonesia is a high-value export-oriented open-access artisanal fishery (> US $150 M: Anonymous, 2007) that occurs throughout the country. It catches up to six species of *Panulirus* and several Scyllarids, with the most important species varying regionally. Southern Java is one of the more productive regions, contributing up to 10% of the national catch (Anonymous, 2007). The fishery in southern Java is unusual as it has two sectors. A tangle trap (krendet) sector undertaken by part-time artisanal fishers from coastal cliffs and an inshore bottom gillnet sector that operates from small (< 10 m) vessels. The fishery catches six species of *Panulirus*, with the majority being *Panulirus homarus* and *Panulirus penicillatus* (Milton et al., 2012). Each sector catches different proportions of each species, with the inshore krendets catching mostly the reef-dwelling *P. penicillatus*. The gillnet sector fishes in deeper water (25–100 m) and mostly catches *P. homarus*, with some *P. versicolor* and *P. longipes*. There is minimal management of the fishery, although catch data are collected from gillnet fishers who sell their catch at government fish auction centres.

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Local knowledge of fishers, collectors and processors in southern Java suggests that the lobster catch has been declining for several years. Management of the fishery is vested in the Provincial government, although the catch data collected are sent to Jakarta for inclusion in national statistics. In order to assess the viable management options for this regional fishery, there is a need to understand the potential for local management actions to influence catch, given the widespread distribution and long larval phase of each species.

Fishers hypothesise that lobster catches increase following heavy rain at the commencement of the monsoon season. Monsoon runoff increases coastal water turbidity and lobsters appear to leave shelter and thus become more catchable (Milton et al., 2012). If this relationship is strong, then reduced catches may potentially be related to changes in rainfall patterns or intensity and be independent of fishing effort.

Management options available for open-access fisheries such as the lobster fishery include spatial or temporal closures, lobster size or fishing effort restrictions and introduction of user rights (Gelcich et al., 2012). Some understanding of the lobster population structure would help identify the option with the greatest likelihood of improving local catch sustainability. The importance of local climate in influencing catch will also influence the most viable management option. The aims of this study were to (1) examine reproductive seasonality in lobsters to identify the main spawning period, (2) assess the linkage between fishery catch rates and local environmental conditions and (3) construct a larval advection model to predict the level of self-recruitment in the southern Java fishery in order to identify potential local management options.

2. Materials and methods

2.1. Study area

The lobster fishery in southern Java occurs mostly along the coast east of Yogyakarta. The main fishing grounds occur in the Gunung Kidul and Pacitan regencies in D.I. Yogyakarta and East Java Provinces respectively (Fig. 1). Climate in the region is dominated by the tropical monsoon, with most rainfall in the period October to March. The coast is characterised by extensive highly eroded limestone cliffs ($\sim$20 m). The coastal shelf ($<$100 m depth) is narrow ($<$5 km) with numerous coral and rocky reefs that are fished by a variety of artisanal line and net fisheries.

2.2. Sampling

Seven surveys of lobster collectors and fish landing sites were made between March 2010 and October 2012. During each visit, all landing sites and lobster holding facilities (collectors) in the study area were visited. Landing sites were visited in the early morning as fishers returned from the sea. Each vessel was intercepted at the beach and its catch processed. Lobsters were identified, sexed, weighed ($\pm$0.2 g) and measured (carapace length$\pm$1 mm). Females were examined closely for the presence of scraped off spermatophore “tar spots” or eggs. Where females were found to be bearing eggs, the stage of egg development based on size and colour was also noted (Milton et al., 2012).

The same details were obtained for lobsters held in lobster processor facilities. Processors were also asked to identify the proportion of the lobsters in their facility that were collected by krendets or from fishers with gillnets and krendets in boats. We attempted to estimate daily lobster catch rates by asking each collector to indicate how many days the lobsters in the facility had taken to accumulate. Repeated visits to a subset of collectors on consecutive days supported their estimates of turnover rates (Milton et al., 2012).

2.3. Advection model

The sources of puerulus that recruited to the fishery were examined for the period 1993–2007 with a regional oceanographic model of larval advection (http://www.csiro.au/connie2/: Condie and Andrewartha, 2008; Condie et al., 2005; 2006; 2011). The model uses surface and sub-surface currents estimated from satellites and tide-gauge estimates of sea level in combination with modelled wind fields. Griffin et al. (2001) and Condie et al. (2005) have extensively tested and validated the approach against ocean drifter data in the Australian region. Current velocities were computed from the sea level fields by the geostrophic approximation. A wind-driven velocity component was added with a surface Ekman layer dynamics model (Pollard and Millard, 1970) and winds obtained from the NCEP-NCAR 40—yr Reanalysis dataset (Kalnay et al., 1996). It also incorporates a three-dimensional component that was resolved between 3 and 200 m (see Condie and Andrewartha (2008) for details). It also incorporated temperature and salinity fields interpolated from the global circulation BlueLink Ocean ReANalysis model (Schiller et al., 2008).

For each year, one million particles were seeded at random within the release region (between Baron and Drini: 100 km^2) during the spawning period (November–March) and allowed to move at 8 h intervals according to the interpolated current velocity (Condie et al., 2005). Particles in the model were released at a depth of 5 m in the water column. Plankton studies have shown that *Panulirus* larvae undertake diel vertical migration (Dennis et al., 2001). The model allows diel vertical migration to be incorporated in the predictions. We set the daytime depth of our particles at 100 m (Feng et al., 2011), returning to 5 m at night following the results of Dennis et al. (2001). No change in diel migration with larval age (Butler et al., 2011) was feasible. The particle advection period was set at 200 days, based on available data for *Panulirus homarus* and *P. penicillatus* from other regions (Booth and Phillips, 1994; Matsuda et al., 2006; Phillips et al., 2006).

2.4. Environmental factors

During preliminary independent discussions with a large number of fishers and collectors, most indicated that they observed a strong relationship between lobster catch and the intensity of the monsoon rainfall. To test the hypothesis that lobster catch increased with the onset of the monsoon, we obtained weekly rainfall for southern Java since 2001 from the Indonesian Agency for Meteorology, Climatology and Geophysics (http://www.bmkg.go.id) (BMKG). Daily lobster catch data of *P. homarus* and *P. penicillatus* were available for the period 2001–2010 at two landing sites about 30 km apart—Drini and Baron (Fig. 1). Fishing effort and catch rate data were only available for a shorter period (2007–2011). Weekly temperature and Southern Oscillation Index data were also obtained from BMKG. Monthly mean SST and SST anomalies were obtained from NOAA interpolated to a 50 km^2 grid (http://www.class.ngdc.noaa.gov/saa/products/search?datatype_family=SST50).

2.5. Data analysis

The larval advection model had a resolution of 0.1°. The main summary output for each cell is the predicted proportion of the particles that had been sourced from each 0.1° cell within the model boundaries (20°N–65°S and 90–180°E) (Condie et al., 2005). Thus, we could examine the fate of particles sourced from the study area (source) and those that ended the larval period in the study area (sink). As the southern coast of Java is orientated east-west, we