Appendix 1
Arkema, K. K., L. A. Rogers, J. Toft, A. Mesher, K. H. Wyatt, S. Albury-Smith, S. Moultrie, M. H. Ruckelshaus, and J. Samhouri. 2018. Integrating fisheries management into sustainable development planning. *Ecology and Society.*

METHODS

To assess fisheries outcomes of alternative scenarios for Coastal Zone Management in Belize and Development Planning in The Bahamas, we combined quantitative modeling and stakeholder engagement. Our workflow began with stakeholder driven scenarios of coastal and marine uses that we then compared by assessing cumulative risk to nursery and adult habitats using a risk assessment approach. Next we estimated the amount of lobster habitat in areas of high, intermediate, and low risk, and finally input these estimates of functional lobster habitats into the InVEST fisheries model to estimate catch and revenue of lobster under different scenarios of human use (Figure A1.1).

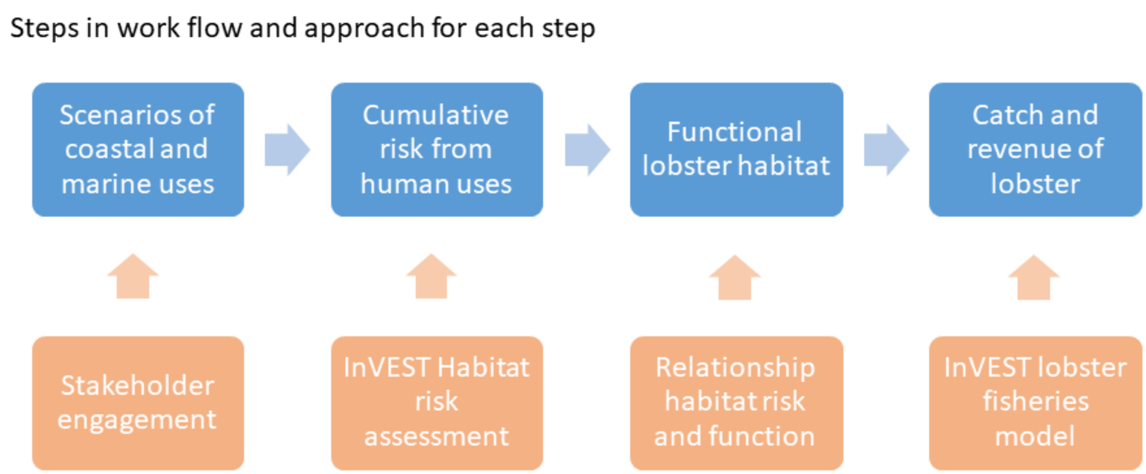

Figure A1.1: Conceptual diagram showing the steps in the workflow (blue boxes) and approach taken within each step (orange boxes).

Model documentation

To estimate how changes in habitat influence catch and revenue from the lobster fishery, we developed a model that incorporates life history, recruitment, migration, harvest, mortality, and habitat dependencies, and produces estimates of catch (as landings and export value) at national and subregional scales (Arkema et al. 2015, Ward et al. 2018). The population model is spatially explicit and age-structured with a Beverton-Holt spawner-recruitment relationship (see Equation S1 in Arkema et al. 2015). By linking recruitment or survival to habitat availability, the model can be used to assess how changes in habitat could affect productivity of the stock and resulting catch. Full model documentation, including inputs and data sources, is in the appendix of this paper and the supplement of Arkema et al. 2015. The model is also available for download as part of the InVEST suite of ecosystem services models (Sharp et al. 2018). The main differences between the models used in Belize and the Bahamas are summarized in Table A1.1, and more detailed descriptions appear below it.

Table A1.1 Summary of differences in model features for lobster population dynamics in Belize and the Bahamas.

Model Feature	Belize	Bahamas
Influence of habitat on lobster population dynamics	Mediated via survival during transitions between life stages (larval to juvenile; juvenile to adult)	Mediated via maximum potential recruitment at larval settlement
Dispersal to adult habitat	Distance-dependent	Directly proportional to habitat availability
Model fitting	To catch observations	To stock assessment parameters

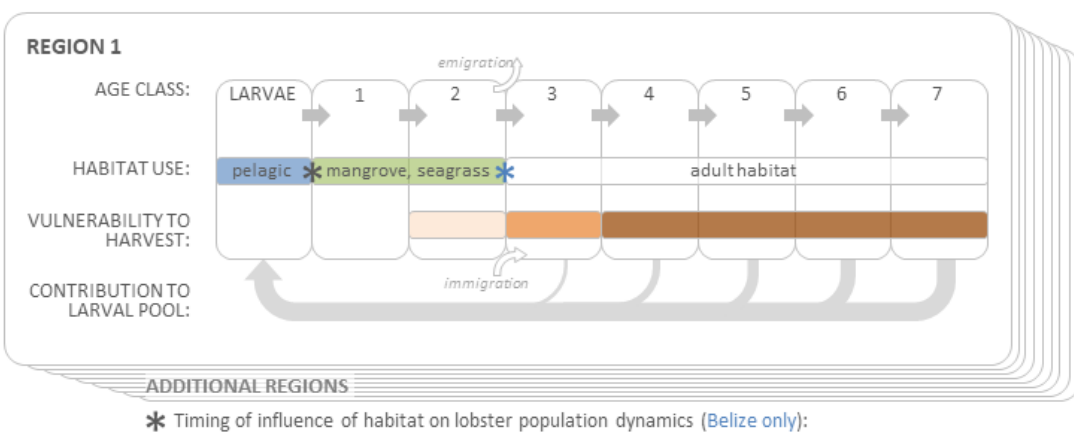

Figure A1.2 Conceptual diagram of lobster model where the asterisks indicate where habitat transitions occur that affect the lobster dynamics, either via recruitment (The Bahamas; gray asterisk) or mortality (Belize, gray and blue asterisks).

Belize

The model details provided here complement those found in Arkema et al. 2015 Supporting Information Appendix 1 (Ecosystem service models and data/Spiny lobster model), which contains nearly complete model documentation. Equations found there are labeled below as Arkema Eqn. S1-S5, for reference. Parameter values can be found in Table A1.2 below.

Life history parameters - Growth and maturation:

We use a von Bertalanffy growth equation and a length-weight relationship to transform numbers-at-age to weight-at-age, w_{age}:

$$w_{age} = a\, L_{age}{}^{b}$$

where:

- a, b are parameters of the von Bertalanffy growth equation
- L_{age} is length-at-age

We estimated a and b and by minimizing the residuals between observed weights for ages 1-9 (Puga et al. 2005) and predicted weights (using L_{age}).

L_{age} is defined as:

$$L_{age} = L_{\infty}(1 - exp(-K(\text{age} - t_0)))$$

where:

- L_{∞} is the asymptotic maximum length
- K is a curvature parameter, which is proportional to the rate at which L_{∞} is reached
- t_0 is the age at which the fish has 0 length, therefore, is non-negative, or zero.

Spawner biomass is the product of numbers of lobster in each region (Arkema Eqn. S1), weight at age(w_{age}), and maturity at age (m_{age}), which is calculated using a maturity ogive governed by a logistic function:

$$m_{age} = (1 + exp(-\phi(L_{age} - L_{50})))^{-1}$$

where:

- ϕ determines the slope of the logistic function
- L_{50} is the length-at-50% maturity
- L_{age} is length-at-age, defined above.

Recruitment parameters

Recruitment was modeled using a Beverton-Holt function reparameterized in terms of steepness (h), average recruitment in the absence of fishing (R_0), and spawners per recruit (SPR), which is the amount of spawning biomass produced by each recruit in an unfished population and is calculated from life history parameters (Hilborn 2010). The model gives estimated recruits (age 0 lobster) as a function of total spawning biomass (S).

$$R = \frac{4hR_0S}{R_0SPR(1-h)+S(5h+1)}$$

For recruitment, model fitting was conducted with time series of catch and CPUE (as described in full in the supplementary materials of Arkema et al. 2015).

Harvest parameters - Vulnerability to harvest:
We modeled vulnerability-at-age to harvest, v_{age}, by using the logistic function:

$$v_{age} = 1/(1+exp(-(\text{age}-a_{50})*\delta))$$

where:

- a_{50} is the age at which individuals have a 50% vulnerability to harvest
- δ determines the slope of the logistic function

The δ we chose gives the shape of the logistic function near knife-edge selectivity, meaning that very few lobster younger than 2.5 years (i.e., a_{50}) are vulnerable to fishing, whereas almost all lobster older than 2.5 years are vulnerable to fishing. This cutoff was chosen as this is the average age - modeled as described in A.1 - when a lobster reaches the minimum legal size for harvest of 75mm. Vulnerability to harvest was assumed to be the same across regions (Table A1.2).

Harvest rate:
Exploitation, or harvest rate, was assumed to remain constant and the same across all regions. It was calculated by dividing the modeled 2010 harvestable biomass by the observed 2010 catch (Table A1.2).

Catch to value conversion:
We calculated total pounds of harvestable lobster as the product of the numbers-at-age, weight-at-age, vulnerability-at-age to harvest, and harvest rate to arrive at total pounds of catch. Observed landings were reported as total pounds of tail meat. To compare model predictions to observations, we converted total pounds of catch by applying a conversion factor - proportion of total catch that is tail meat, from records of pounds of whole lobster landed (FAO 2001) and lobster tail production (Belize Fisheries Department Annual Report 2008) from 1947-1995 (Table A1.2).

Gross export value ($BZ) of tails was calculated as the product of pounds of lobster tail production, proportion of tails landed that were exported in 2010 (Belize Fisheries Department 2012), and the price-per-pound for lobster tails exported in 2010 (Belize Fisheries Department 2012; Table A1.2).

Movement parameters - Larval dispersal
Larvae were assumed to mix across all regions during their extended pelagic period, then settle in nursery habitat in direct proportion to its availability across all regions (i.e. a region with 12% of nursery habitat received 12% of recruits; also see Gariavelli et al. 2017).

Migration
Movement between regions was modeled as described in Arkema et al. 2015 (S1) when lobsters transition from age 2 to age 3, as they move from mangroves and seagrass habitats to coral reefs (Marx and Hernkind 1986). The lobsters move from the region they have occupied at age 2 to other regions. The amount of movement is determined by an exponential decay weighted by the proportion of coral reef habitats in the region relative to the whole country. Distance was calculated as the distance between centroids of each region. The decay rate was estimated by finding the value for it that minimized the residuals between modeled biomass in each region and reports from the Belize Fisheries Department of observed catches by region (*R. Carcamo, pers. Comm.*; Table A1.2). Observed catch was reported by fishing areas of Belize, which are similar yet not identical to regions used in modeling. Accordingly, we reapportioned catch to model region based on areal extent of fishing areas and regions.

Linking changes in habitat to lobster dynamics
In the Belize model, lobster survival was affected by habitat availability as lobster transitioned from one habitat to another, specifically during larval settlement to nursery habitat, and during the transition to coral reefs. Survival from one age class to the next was a function of natural mortality rate, change in habitat availability during transitional ages, degree to which survival during transition depends on habitat availability, and a shape parameter for a habitat dependency logistic function (Arkema Eqn. S2). We assumed that survival during transitions between habitat was strongly dependent upon availability of habitat which could be changed in future scenarios.

Survival during transitions depended on habitat availability that in turn varied spatially based on the cumulative risk of degradation from human activities within and across ICZM scenarios. Habitat at high risk was assumed to no longer be functional for spiny lobster and was excluded from calculations of future habitat area; habitat at medium risk was assumed to be 50% functional, thus contributing half its area to future area calculations; habitat at low risk was assumed to be fully functional (Arkema et al. 2015).

Model validation
The Belizean Fisheries Department provided limited empirical information on spatial variation in catch (R. Carcamo and M. Canto, pers. comm. 2013). The fishing regions delineated by the Fisheries Department do not directly correspond to the nine ICZM planning regions, and therefore preclude a quantitative comparison of modeled versus empirical catch; however, we made a qualitative comparison across areas (Figure A1.4).

Table A1.2 Key inputs to Fisheries Production models for spiny lobster (Belize and Bahamas)

	BELIZE		**BAHAMAS**	
INPUT	**Value**	**Source**	**Value**	**Source**
Life history parameters				
Growth				
Length-at-age	L_∞=180 mm, K=0.24, t_0 = 0.44	de Leon González et al. 2008	L_∞=180 mm, K=0.24, t_0 = 0.44	
Weight-at-age	a = 2.33E-06, b = 2.91	Estimated; See A.1.	a = 2.33E-06, b = 2.91	
Maturation parameters	L_{50} = 80 mm, ϕ = 0.3	Little and Watson 2005	L_{50} = 80 mm, ϕ = 0.3	Little and Watson 2005
Mortality rate	M = 0.36	de Leon González et al. 2008	M = 0.36	2012 Stock Assessment
Recruitment parameters				
Steepness	h = 0.9746	Estimated; See Arkema Table S4, Fig. S15.	h = 0.8	2012 Stock Assessment
Initial recruitment	R_0 = 4,724,899	Estimated; See Arkema Table S4, Fig. S15.	R_0 = 64,524,000	Estimated in model
SPR (Spawners per Recruit)	2.64	Estimated using catch data and life history information	2.64	Calculated from life history
Harvest parameters				
Vulnerability by age	a_{50} = 2.5; delta = 10	Calculated; see A.3	a_{50} = 2.5; delta = 10	See A.3.
Exploitation rate	Ex = 0.309	See Arkema Eq. S4, with E_x = 0	Ex = 0.167 (F=0.183)	2012 Stock Assessment
Price per lb (tail meat)	PPP_{tail} = \$29.93	Belize Fisheries Department 2012; See Arkema Eq. S5	\$10.86	Average export price (1997-2014) from DMR
Proportion of total catch that is tail meat	0.32	Calculated; see A.3; See Arkema Eq. S5	0.36	2012 Stock Assessment
Proportion of tails landed that were exported	0.89	Belize Fisheries Department 2012; See Arkema Eq. S5	N/A	N/A
Movement parameters				
Distance decay rate	0.11	Estimated; see A.4	N/A	N/A
Habitat transition	T_1, T_3 = 1; all other T_a = 0	Marx and Hernkind 1986; See Arkema Eq. S2	N/A	N/A
Habitat dependency during transition	d = 1	Marx and Hernkind 1986; See Arkema Eq. S2	N/A	N/A
habitat dependency logistic function shape	γ = 0.5	Assumption based on lack of information; See Arkema Eq. S2	N/A	N/A
Habitat distribution				
Seagrass	Area of seagrass within each planning region	Coastal Zone Management Institute of Belize (CZMI	Area of seagrass within a 1km buffer of the coastline	Interpretation of Landsat Imagery, 30m, 2005

		1997) and Mesoamerican Reef Millennium study (Wabnitz et al. 2007)		
Mangroves	Area of mangroves within each planning region	2010 CATHALAC / WWF	Area of mangroves within a 250m buffer of the coastline	Interpretation of Landsat Imagery, 30m, 2005
Coral reefs	Area of coral reefs within each planning region	1999 Coastal Zone Management Institute of Belize (CZMI) and Peter Mumby	N/A	N/A
200m Bank area	N/A	N/A		Landsat

The Bahamas

The Belize model was adapted for the Bahamas, keeping much of the same form as described in Arkema et al. 2015. However, some modifications were necessary to incorporate different data sources and assumptions relevant to the decision context.

Life history parameters - Growth and Maturation
Parameters describing growth and maturity were assumed to be the same as for the Belize model, which is reasonable given the uncertainty in estimating these parameters for spiny lobster across the Caribbean (Leocadio and Cruz 2008; Table A1.2).

Recruitment parameters
We used life history information and output from the Bahamian 2012 national stock assessment for spiny lobster (Medley and Gittens, 2012) to parameterize the stock-recruitment function in our model. Steepness (h) was set to 0.8 as in Medley and Gittens (2012), and spawners per recruit (SPR) was estimated from life-table data including age-specific maturity, natural mortality, and weight at age (Table A1.2). The final parameter (R_0) was estimated by setting the harvest rate equal to that estimated in the assessment, and then solving for R_0 such that the amount harvested was equal to total 2010 harvest in the assessment (Table A1.2).

Harvest parameters - Vulnerability to harvest
Lobster age 3 years and older were assumed to be vulnerable to harvest, following Medley and Gittens (2012) and based on the expected age at the minimum legal size (83 or 85 mm). We thus used the same vulnerability function as in the Belize model, which gives near knife-edge selectivity at age 2.5.

Harvest rate
Exploitation, or harvest rate, was assumed to remain constant and equal to that estimated in the Medley and Gittens (2012), and to be the same across all regions (Table A1.2).

Catch to value conversion
To estimate the export value of lobster catch, we used the estimated proportion of total lobster catch that reached market (i.e. the tail) and the average export price per processed pound of lobster from 1997 - 2014 (Department of Marine Resources; Table A1.2).

Movement parameters - Larval Dispersal
Larvae were assumed to disperse throughout the Bahamas, and settle in a region in proportion to the amount of nursery habitat in that region relative to the entire Bahamas, as in the Belize model.

Migration
As in the Belize model, migration from nearshore juvenile nursery habitats (mangroves and seagrass) to offshore adult habitat occurred from age 2 to 3. Because of the prevalence of casitas (artificial habitats deployed by fishermen to aggregate lobster), we assumed that adult habitat was any area on the shelf up to 200m depth and not constrained to coral reefs. Lobster were assumed to move from nursery to adult habitat and distribute evenly throughout contiguous shelf areas. A distance-decay function was not implemented in the Bahamas.

Linking changes in habitat to lobster dynamics
For development scenarios, recruitment was assumed to be directly proportional to the amount of nursery habitat available, which was implemented by varying the parameter R_0 in the stock recruit relationship. For instance, a 10% reduction in total nursery habitat would reduce R_0 by 10%, thus reducing the maximum potential recruitment to the stock. This is consistent with the assumption that recruitment is habitat-limited (Butler and Herrnkind 1997).

Model Validation
Given the lack of time-series data with which to fit our model, we sought to validate model estimates using available historical data. Recent survey-based estimates of lobster abundance do not exist; however, an earlier study based on widespread sampling on the banks estimated the density of lobster on the Little and Great Bahama Banks as 420 and 287 kg/km2 respectively (Smith and van Nierop 1986). The model estimated the current density of lobster to be 365 kg/km2, suggesting that the biological output of the model is reasonable. It is not known whether current lobster densities are greater or less than in 1986, although fishing pressure has likely increased since the 1980s.

Table A1.3 Data originate from multiple sources, including from partners at The Nature Conservancy (TNC) and Bahamas National Trust (BNT)'

Human Use and Drivers of Change	Data Sources	Description
Development	Digitized aerial imagery (TNC), stakeholder drawn maps, local expertise	Spatial footprint of development, which included private, residential, and commercial development, roads, lodges, airports, factories, airports and more.
Dredging and mining	Digitized aerial imagery, stakeholder drawn maps, local expertise	Spatial footprint of terrestrial quarries for sand, aragonite and other minerals; and dredged marine channels for transportation, often near ports
Nature-based tourism	TNC, Andros Island Conservation Assessment, BNT	Areas identified during stakeholder engagements including areas for diving, bonefishing, bird watching, kayaking etc.
Transportation of goods and people by water	Marine Automatic Identification System (AIS), Stakeholders	Buffered polylines of routes by ferries, mail boats, and cargo ships. Personal transportation and fishing vessels are not included.
Fishing	Area of interest	Fishing for lobster, conch, scalefish, and sponge. Stakeholders and local experts identified that fishers use the entire area of interest.
Forestry	Department of Forestry	Parcel designations for conservation forests (not to be harvested), forest reserves (for timber use), and protected forest (that can be converted for development).
Agriculture	Digitized Aerial Imagery (TNC), Dept of Forestry	Spatial footprint of large-scale (e.g. for BAMSI and otherwise zoned) and small-scale, agriculture.
Invasive Species	Andros Island Conservation Assessment, U.S. Geological Survey	Invasive species point data location for *Melaleuca*, *leucaena*, and *Casuarina* buffered by 750m where density was reported as sparse or dense. Lionfish are represented across the coral reef, based on observations reported to USGS.
Sea-level rise	Allen and Holding 2015	*Not included in the current scenario.* Area affected by 2m of sea-level rise. Digitized from Allen and Holding 2015.
Protected Areas	TNC, BNT	Protected areas as defined by the Bahamas National Trust (BNT), both terrestrial and coastal

RESULTS

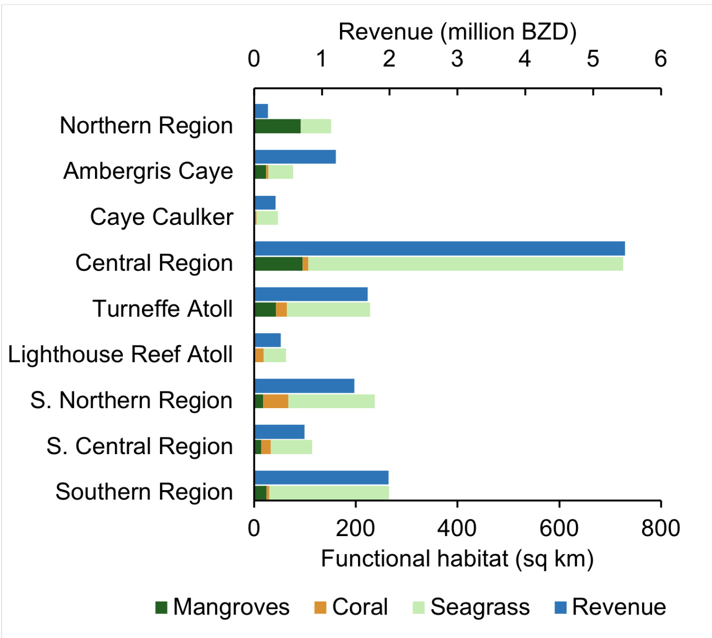

Figure A1.3 Modeled lobster revenue and area of each habitat type in Belize by planning region in 2010, the *Current* scenario.

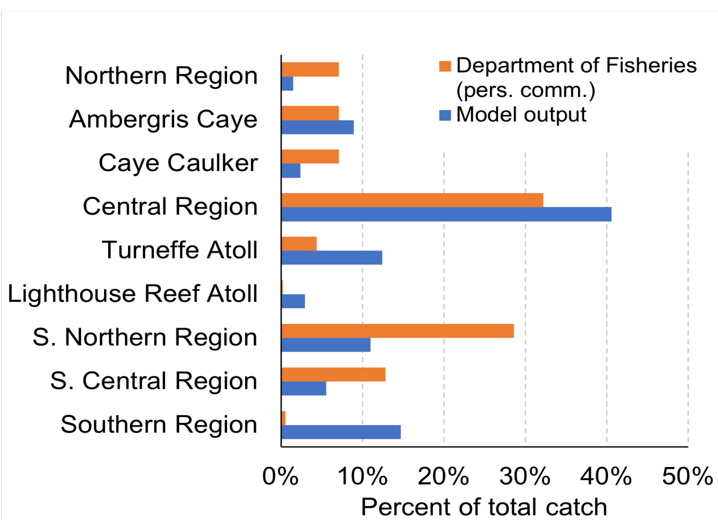

Figure A1.4 Qualitative comparison between empirical information on spatial variation in catch from the Belize Fisheries Department and modeled catch by planning region for the *Current* scenario.

ADDITIONAL LITERATURE CITED

Belize Fisheries Department. 2012. Belize Fisheries Department Capture Fisheries Unit, Annual Report 2011. Belize City, Belize. February 23, 2012.

de Leon González, M.E., Carrasco, R.G., and R.A. Carcamo. 2008. A Cohort Analysis of Spiny Lobster from Belize.

FAO (Food and Agriculture Organization of the United Nations). 2001. FAO Fisheries Report No. 619. Western Central Atlantic Fishery Commission. Report on the FAO/DANIDA/CFRAMP/WECAFC regional workshops on the assessment of the Caribbean spiny lobster (*Panulirus argus*). Part II, Chapter 2. National report on the spiny lobster fishery in Belize; Fig. 2.4.

Leocadio, A. M. Cruz. R. 2008. Growth parameters of the spiny lobster (*Panulirus argus*) in the great Caribbean: A Review. *Rev. Invest. Mar*, *29*(3), 239-248.

Little, S.A. and W.H. Watson III. 2005. Differences in the size at maturity of female american lobsters, *Homarus americanus*, captured throughout the range of the offshore fishery. *Journal of Crustacean Biology* 25(4): 585-592.

Marx, J.M., and W.F. Herrnkind. 1986. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (south Florida) - spiny lobster. U.S. Fish Wildlife Service Biological Reports 82(11.61). U.S. Army Corps of Engineers, TR EL-82-4. 21 pp.

Puga, R., Hernández S., López J and León M.E. de. 2005. Bioeconomic modeling and risk assessment of the Cuban fishery for spiny lobster *Panulirus argus*, *Fisheries Research* 75: 149–163.