How Low Can You Go? Setting Minimum Stocking Densities for Sea Cucumbers Using an Agent-based Movement Model

¿Qué tan Bajo Puedes Llegar? Estableciendo Densidades Minimas de Bancos de Pepinos Marinos Usando Herramientas de Modelaje Espacial

Faible Comment Pouvez-vous Aller? Détermination de Densités Minimales d'Ensemencement de Concombres de Mer À l'Aide d'Outils de Modélisation Spatiale

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EXTENDED ABSTRACT

A recently developed fishery for sea cucumbers (Class: Holothuroidea) is delivering a novel income stream to fishing communities in many areas of the Caribbean. The high value of sea cucumbers when exported to Asia combined with the low technology of the fishery means that there are few barriers to entry. If correctly managed, this low-trophic level fishery promises to deliver a high-profit, high-yield natural product. However, sea cucumber exploitation in other regions has been characterised by "boom and bust" scenarios, as management strategies have not been put in place to prevent rapid depletion of the breeding population.

A key scientific challenge in developing fisheries management strategies for sea cucumbers is that the animals are slow moving, which induces Allee effects by accelerating population decline once a population density threshold is passed. In other words, the probability of individuals encountering potential mates decreases as density drops, leading to population collapse through reproductive failure. Sea cucumber population dynamics thus have spatial as well as demographic components, limiting the value of traditional population/stock models (e.g., matrix models, differential equation models) in setting sustainable quotas.

To tackle this challenge, we used published data to create a prototype agent-based model (ABM) of sea cucumber spatial dynamics. ABMs are computational models comprising a virtual world populated by individual *agents* (Grimm et al. 2006). The agents are programmed to behave in a manner that replicates the natural system being studied, and the interactions among the agents scale up to produce the population-level patterns that can be seen in nature. ABMs are now widely used to study individual-based systems in fields as diverse as political science, economics, cell biology, and particle physics, and are providing deeper insights to the behaviour of complex natural and social systems than was previously possible.

The prototype ABM we present here renders sea cucumbers as agents within a 1 ha benthic plot (Figure 1). Each sea cucumber agent uses empirically derived biological parameters in order to grow, move and aggregate to reproduce in response to moon phase. Note that sea cucumber *aggregations* usually involve 2 - 5 individuals and are not to be confused with mass spawning aggregations observed in many reef fishes. The parameters that define and control the agents may be divided into three classes: calibration, biological and behavioural (Table 1). Calibration parameters are defined by the user to adapt the model for site-specific conditions, such as local population density and size-class structure. Biological parameters were developed using published demographic data for *Isostichopus badionotus*, the Caribbean sea cucumber species on which many Caribbean fisheries are based. However, we do not at present have sufficiently detailed behavioural data for *I. badionotus*, and so the prototype ABM uses parameters for the Indo-Pacific species, *Holothuria scabra*, which is of similar body size. There are fundamental ecological differences between Indo-Pacific and Caribbean species and reef systems and so in order to establish scientifically rigorous results upon which to base management recommendations we will calibrate the ABM for Caribbean species and validate the results against field observations. Calibration and validation fieldwork will begin in April 2015, and will involve characterising the aggregation behaviour of *I. badionotus* across a sequence of lunar cycles at Cayos Cochinos in Honduras. Once the ABM has been validated, we will identify threshold population densities below which breeding success of sea cucumber is likely to be impaired. Further work will involve modifying the ABM for use with other slow-moving benthic organisms, including queen conch, *Strombus gigas.*

KEY WORDS*: Bêche-de-mer,* sandfish, stock assessment

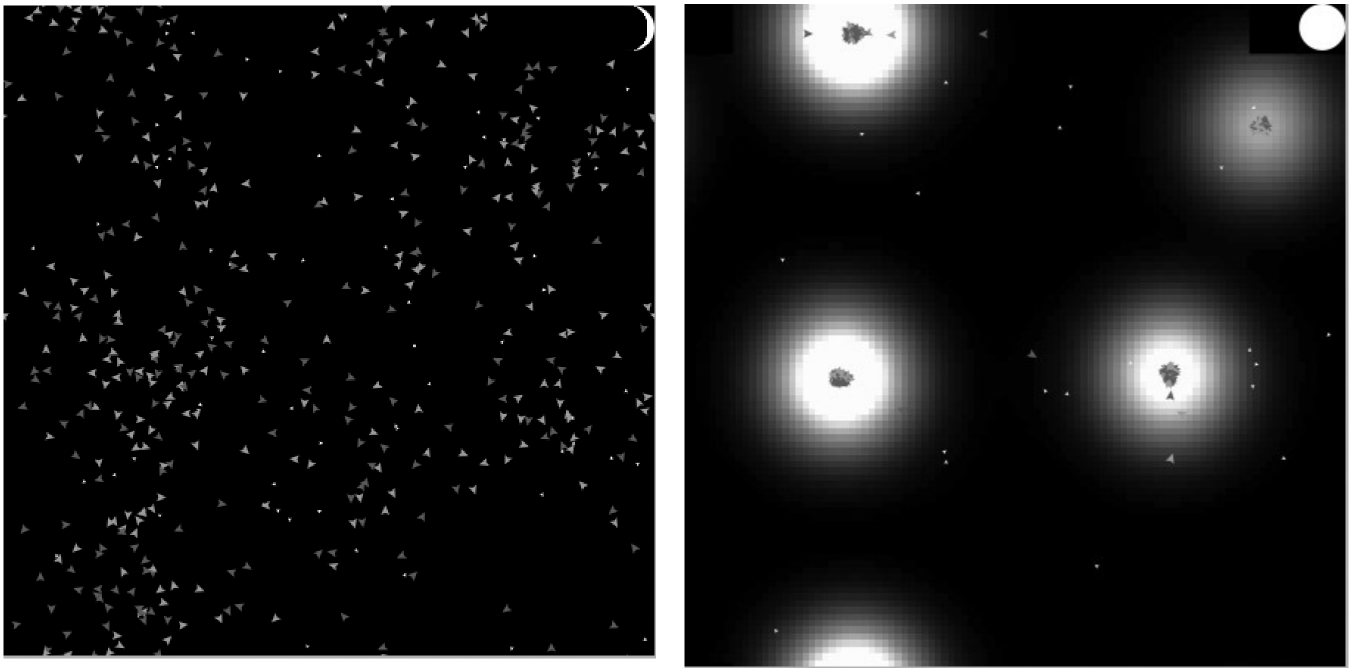

Figure 1. Screenshots of the prototype sea cucumber agent-based model (ABM), which has been constructed using empirical growth data for Caribbean species and behavioral data for Indo-Pacific species. Each panel represents 1 ha of marine benthos viewed from above, and sea cucumbers are displayed as white points against the black benthos. Model moon phase can be seen in the top right of each panel. **Left panel:** At new moon, individuals do not aggregate but simply forage and sleep according to empirical behavioral rules. **Right panel:** As full moon approaches, individuals aggregate to spawn, shown here using a heat map where increasing density is displayed on a gradient from black to white. The number of aggregations is determined by the strength of chemical attraction among individuals.

Table 1. Parameters used to initialise and run the agent-based model for local sea cucumber populations.

Parameter Class	Attribute	Data Source
Biological	Somatic growth rates	Poot-Salazar et al. 2014
	Size at maturity	Zacarías-Soto et al. 2013
Behavioural	Turning angle probabilities	Purcell and Kirby 2006
	Mass-specific movement speed	Purcell and Kirby 2006
	Aggregating tendency	Mercier et al. 2000
Calibration	Chemical diffusion rate	Scheduled field study
	Sex ratio	User defined
	Size class structure	User defined
	Density	User defined

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