Modeling fish dynamics around FADs

JL Deneubourg (ULB), L. Dagorn (IRD) & K. Holland (University of Hawaii)

PFRP Principal Investigators Workshop
University of Hawaii, Honolulu
November 13-14, 2007
OUTLINE

- Aggregation
  - Generic concepts
  - Homogeneous and heterogeneous environment

- Modelling

- Interaction artificial agents-animals
  - Mobile robots
  - Autonomous heterogeneities
Mechanisms

- In heterogeneous environment: same response of the individuals to the environmental heterogeneities
  - Ecologists

- Social interaction
  - Clustering around a leader (individuals are different)
  - Inter-attraction between “identical” individuals (signals or cues identical)

  Homogeneous environment

  - Highly widespread from unicellular societies to mammals group
  - Large functional diversity (reproduction, feeding,...)
  - Permanent or transitory
  - Immobile to highly mobile (school, shoal)

Social interaction is often associated to response to the environmental heterogeneities.

(Camazine et al, 2001)
Spatial heterogeneities

Kinesis: Speed (Temperature) ≈ (T_M - T)^2

Spatial distribution is density independent
Leaders

Workers  Queen
Lasius niger
N = 100
T = 2’30”

Interattraction

(From Depickère)
Lasius niger

N = 100

(From Depickère et al)
By-product of aggregation: collective choice, sorting, synchronization,....

Collective choice

100 lux

75 lux

Proportion of cockroaches under the dark shelter

Individual: 55% in dark

70% in dark

Fraction of experiments

Canonge et al, in prep

Modified from Lebohec et al

Sorting

(Nursery)
Aggregation in heterogeneous environment

Modeling aggregation around FAD

The models are TOOLS

➢ To analyze the relation between individual behavior, population parameters (density) and environmental characteristics AND the spatio-temporal organization of the population around FADs → to integrate different types of data (acoustic data + tagging data)

➢ To use the FADs to make prediction e.g. : is it possible to estimate the total fish density measuring the populations around FAD?
Theoretical tools

• Ordinary differential equations (ODE)

\[
\frac{dx_i}{dt} = Birth - death = F_i(x_1, \ldots, x_n) \quad i = 1, \ldots, n
\]

• Partial differential equations (PDE) : Advection-diffusion-reaction model

\[
\frac{\partial x}{\partial t} = Movement + Birth - death
\]
\[
\frac{\partial x}{\partial t} = D \frac{\partial^2 x}{\partial x^2} + D \frac{\partial^2 x}{\partial y^2} - \lambda x
\]


Analytical treatment (Stability analysis,... ) + numerical solution

• Fluctuation : Stochastic simulation (individual based model)
  Master equation

(Camazine et al., 2001)
Aggregation in heterogeneous environment
Time evolution of the population around each FAD $x_i$

*Individual probability of reaching/joining FAD $i$*

*Individual probability of leaving FAD $i$*
Aggregation in heterogeneous environment

Numerical model: Simple lattice

Differential equation: dynamics of $x_i$ and behavior

$$\frac{dx_i}{dt} = -Q_i x_i + \sum_{j}^{nb} \frac{Q_j x_j}{4}$$
Model 1: No interaction between the fishes

FADs are identical

Three parameters: fish population, resting time around FAD ($\tau_F$), resting time in others cells ($\tau_O$)

Stationary state: Population around each FAD $\approx$ Total population

$$x_1 = \ldots = x_n$$

Stationary state

$$\tau_{fad} = 5 \tau_{\text{open ocean}}$$

Comparing different FAD density $\rightarrow$ Fish density

$$\text{Fraction}_{fishfad} = \frac{D_{fad}}{\frac{\tau_O}{\tau_F} + (1 - \frac{\tau_O}{\tau_F})D_{fad}}$$
No interaction between the fishes (2)

![Graph showing fraction around FAD over time with FADs and FADs are removed annotations.](image-url)
No interaction between the fishes (3)

Point of view of the fisherman

Model → strategy: Optimal density/number of FAD

\[
\text{Benefit} = \frac{\delta D_{fad}}{K + D_{fad}} - \chi D_{fad} \quad D_{opt} = \sqrt{\frac{K}{\delta \chi}} - K
\]

\[\delta = \text{fish density}\]

(R. Hilborn & P. Medley (1999)
Model 2 : Interattraction

\[ \frac{dx_i}{dt} = -Q_i x_i + \sum_{j}^{nb} \frac{Q_j x_j}{nb} \]

\[ Q_i = \frac{\theta}{1 + \beta x_i^n} \]

\[ Q_i = (1 + \beta x_j^n) \]
An easy case study: collective decision making in cockroach group

*Periplaneta americana*

Identical shelters

Φ = 1 m, T = 0 h

T = 3 h

Amé *et al.*, *PNAS* 2006,
Halloy *et al.*, *Science*, November 2007)
Collective decision making in cockroach group based on inter-attraction

Individuals are capable of detecting the shelters and estimate their quality ($\theta_i$). The inter-attraction between individuals decreases the probability of leaving the shelter. 

$$Q_i = \frac{\theta_i}{1 + \rho \left( \frac{x_i}{S_i} \right)^n}$$

$$P_i = \mu_i \left( 1 - \frac{x_i}{S_i} \right)$$

Individuals randomly explore the system & encounter the shelters. They are constrained by a crowding effect.

$x_i$ number of individuals in shelter $i$
$S_i$ carrying capacity of the shelters
$n$ inter-attraction factor ($n \approx 2$)

$x_e$ number of individuals outside the shelters
$p$ number of shelters present in the system
$N$ total number of individuals = $x_e + x_1 ... + x_p$
Collective decision making: experimental bifurcation diagram

Amé et al, PNAS, 2006
Model 2 : Interattraction

\[
\frac{dx_i}{dt} = -Q_i x_i + \sum_{j}^{nb} \frac{Q_j x_j}{nb}
\]

\[
Q_i = \frac{\theta_i}{1 + \beta x_i^n}
\]

Diversity of responses but some generic properties
Influence of the total population or total population estimation from FAD population (1)
Influence of the total population... (2): “selection” of a FAD
2 FADs
Influence of the total population... (3)

(1) Acoustic data + tagging data → Model

(2) Model → Relation between population around FAD and the total population

(3) Data collection with j FADs → estimation of the total population
Influence of the # of FADs
Influence of the # of FADs (2)

50 simulations per condition with random initial conditions (Stationary states)
Mixed societies: mixed groups of social animals and robots. Animals and robots (artificial agents) interact and communicate.

Control means: That it is possible to trigger the emergence of some new global patterns by adding artificial agents with specific behaviors to the society.

\(X_i, A_i\): number of agent \(i\)

Negative feedback  Positive feedback  Flow

Society is a network of interactions.

Living units

Dynamics, attractors

Living units + Artificial agents

New dynamics, new attractors
Lure/Decoy

Bird of prey

≈ 1925-1926
Arctic (Canada)
The artificial agents are passive → The feedback loop is not closed

Function

Patterns
Synchronization, collective choice,…

Beavourial Study
Management & Monitoring

Artificial agents
Mounted devices
Mobile Robots
Network of sensors-actuators
 Mounted devices

Smart collar (Mounted device): GPS, PDA, sound amplifier & wireless networking, affects the behaviour of some individuals & of the group (D. Rus et al, MIT)
What about schools with some fishes tagged with a smart device?
Collective decision making in mixed groups of robots and cockroaches

The lure robots allow the implementation of new feedbacks and the modification of the collective choice (dynamics).

Building interactions and communication:
- Perception of individual presence
- Modulation of the behavior according to individual presence

Robot-insect

Identification analysis

Cuticular hydrocarbons

≈ 40mm

Extraction/Synthesis of the blend
Concentration

Marking

2 Photodiodes
⇒ Shelter detection

12 IR Proximity Sensors
⇒ Cockroach detection
⇒ Wall detection
⇒ Robot detection

C. Rivault, I. Said
V. Durier

F. Tâche, M. Asadpour, A. Colot
G. Caprari, F. Mondada,
R. Siegwart
Summary

➢ Both machines and insects are capable, independently of each other, to perform such collective decision (don’t show here).

➢ The robots are accepted by the cockroaches groups and actively take part in the collective choice. Most of the time, they gather with the cockroaches under the same shelter.

➢ When the robots are programmed to have an opposite preference compared to insects, they are able to induce a change in the global pattern by reversing the collective shelter preference. The mixed group of robots and insects gather in the less preferred shelter by the insects.

G Sempo et al. LNCS, 4095 2006
Experimental demonstration: 12 cockroaches & 4 robots

Shared collective decision between identical shelters

2 shelters: dark & light
Insects prefer dark & Robots prefer light
Network of sensors-actuators: shelters, FADs,...

\[ \frac{dx_i}{dt} = \mu_i x_e - \frac{\theta_i x_i}{1 + \rho \left( \frac{x_i}{S_i} \right)^n} \]

Different patterns, responses of the systems
\[ \rightarrow \text{Information on the total population} \]
\[ \rightarrow \text{Optimal control} \]

\[ \frac{d\theta_i}{dt} = F_i(x_1, x_2, \theta_1, \theta_2) \]
From FADIO (Quality of Life; FP5)
Aggregation-sorting: by-catch

Amé et al, Anim. Behav. 2005
Selective attraction?
Robot-decoy acting selectively on one species e.g. by imitation

Aggregation-sorting: by-catch