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Modeling the Bioaccumulation of a Pharmaceutical Contaminant in a Simple Trophic Web Interaction

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Project Overview

Fig. 2: Bonefish (*Albula vulpes*) swimming in a seagrass bed.
Source: FtLaudGirl, iStockphoto

- Objective: To investigate the bioaccumulation of pharmaceutical contaminants through a simple trophic web interaction, involving one prey and one predator
- Reasoning: Previous study performed by Florida International University displayed the occurrence of pharmaceuticals in the blood plasma of bonefish as well as their prey items (Rehage, Castillo, personal communication 2022).
- Application: To be used as the foundation to model the effects of pharmaceutical contaminants on population dynamics.
- Model:
  - Matches the life history of Bonefish (*Albula vulpes*) and a selected prey item within the South Florida Region.
  - Age-structured population model that separates bonefish into two age classes, juveniles and adults, that both feed on a prey item that grows logistically.
  - Spatially separates the adult bonefish into two areas, with differing chemical loads in the areas

Background

Pharmaceuticals have been shown to remain bioavailable for aquatic organisms for long periods of time, increasing the potential that they could reenter the food web after some time (Lagesson et al 2016). The taking up of pharmaceuticals through the surrounding water is referred to as bioconcentration whereas the accumulation of pharmaceuticals in a fish through both feeding on contaminated prey and the surrounding water is defined as bioaccumulation (Boström et al 2016). Studies performed about the bioaccumulation of pharmaceutical contaminants emphasize that both waterborne exposure and trophic interactions need to be considered when discussing the ecological effect of pharmaceuticals (Ruhí et al 2016). Wu et al. 2020 showed that sulfadiazine and enoxacin were biomagnified along the food web but enrofloxacin, ciprofloxacin, ofloxacin, norfloxacin, and trimethoprim were biodiluted from the food web. There are many discrepancies when it comes to whether respiration or dietary uptake is the primary source of accumulation of pharmaceuticals in aquatic species, thus both factors need to included when discussing the risk of pharmaceutical contaminants in the aquatic environment

Steps to Solve Equations

- The approach used follows a classic method for solving dynamic systems
  - Equilibrium points were found by setting the derivative to zero.
  - The next step is to find local stability using a Jacobian or community matrix
- A set of parameters were chosen from varying literature (Larkin 2011, Huang 2014)
- The equations were graphed using literature found parameters and the mathematical programming software Maple

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Trophic Pathway Diagram

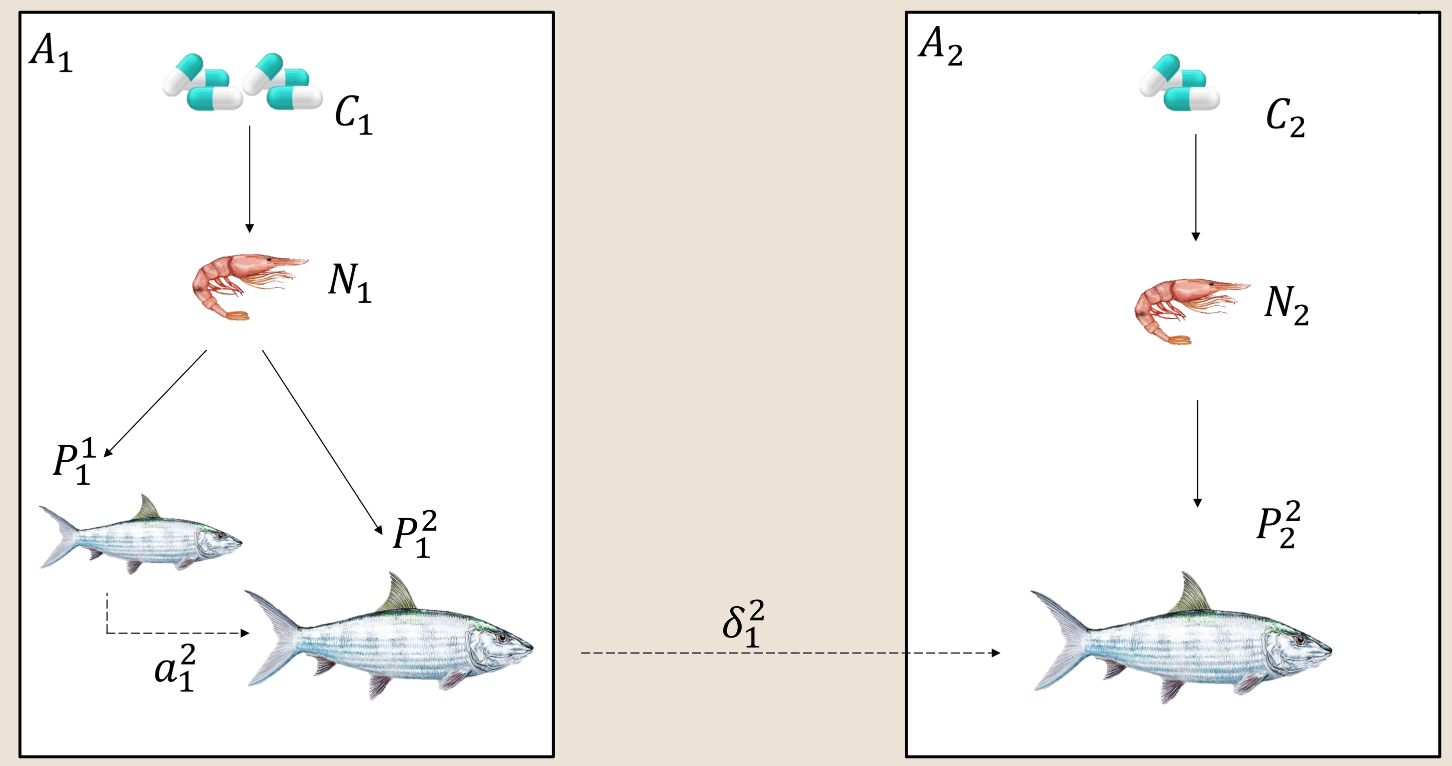

Fig. 2: Box diagram describing the age-structured population model of a bonefish population in two different areas.

Equations

- Growth of prey in this model is logistic where area is a limiting resource
- Predator-prey interaction follows a type II function response (Hollings, 1959)

Prey in area one

$$\dot{N}_1 = rN_1\left(1-\frac{N_1}{A_1}\right)-\frac{E_1N_1P_1^1}{K_{N_1}^1+N_1}-\frac{E_2N_1P_1^2}{K_{N_1}^2+N_1}$$

Juveniles in area one

$$\dot{P}_1^1 = \frac{E_1N_1P_1^1}{K_{N_1}^1+N_1}+\beta P_1^2-a_1^2P_1^1-\mu_1^1P_1^1$$

Adults in area one

$$\dot{P}_1^2 = \frac{E_1^2N_1P_1^2}{K_{N_1}^2+N_1}+a_1^2P_1^1-\delta_1^2P_1^2$$

Chemical load in area one

$$\dot{C}_1^{21} = \lambda_1E_1^2N_1P_1^2-fC_A^{21}-\delta_1^2C_A^{21}$$

Prey in area two

$$\dot{N}_2 = rN_2\left(1-\frac{N_2}{A_2}\right)-\frac{E_2N_2P_2^2}{K_{N_2}^2+N_2}$$

Adults in area two

$$\dot{P}_2^2 = \frac{E_2^2N_2P_2^2}{K_{N_2}^2+N_2}+\delta_1^2P_1^2-\mu_2^2(P_2^2)^2$$

Chemical load in area two

$$\dot{C}_2^{22} = \lambda_2E_2^2N_1P_2^2+\delta_1^2C_A^{21}-fC_A^{22}$$

Chemical Loads in Area 1 and Area 2

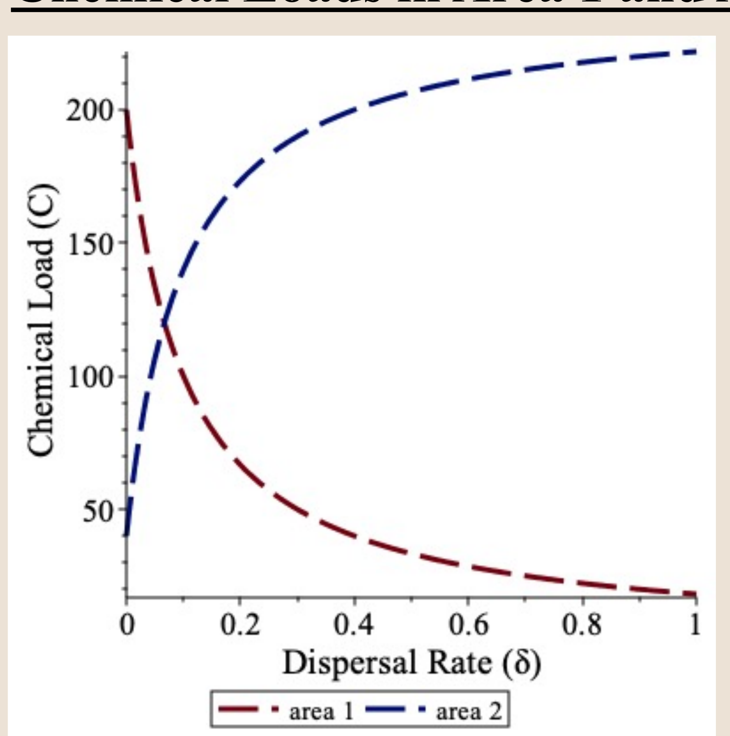

Fig. 3: The following graph displays the chemical load in adult bonefish with differing dispersal rates (δ).

As the dispersal rate increases, more adult fish will swim away from area one, carrying the pharmaceutical load they gained in area one. As the fish swim away from area one, the total chemical load in adult fish in area one will decrease as the total chemical load in adult fish in area two will increase.

Definition of Variables and Parameters

N	Prey	K	Carrying capacity	δ	Dispersal Factor
P	Predator	β	Birth rate (predator)	λ	Chemical Assimilation Factor
C	Chemical	a	Aging Factor	f	Flushing Factor
A	Area	μ	Natural Mortality	P_{area}^{age}	Notation
r	Birth rate (prey)	E	Growth rate		

Equilibriums

Mean chemical load in adults in Area 1

$$\hat{C}_A^{21} = \frac{1}{f\delta_1^2}(\lambda_1E_1^2\hat{N}_1\hat{P}_1^2)$$

The chemical load in adult bonefish in area one increases as the adult bonefish feed on the contaminated prey items. The chemical load decreases as a function of the flushing and dispersal rate.

Mean chemical load in adults in Area 2

$$\hat{C}_2^{22} = \frac{1}{f}(\lambda_2E_2^2\hat{N}_1\hat{P}_2^2+\delta_1^2\hat{C}_1^{21})$$

The chemical load in adult bonefish in area two increases as the adult bonefish feed on contaminated prey items from area two and as bonefish from area one swim into area two, carrying the chemical load from area one. For area two to not depend on the chemical load from area one, the dispersal rate needs to be zero, i.e., no adult movement between the two areas

Adult Population in Area 1

$$\hat{P}_1^2 = \frac{1}{\delta_1^2}\left(\frac{E_1^2\hat{N}_1}{K_{N_1}^2+\hat{N}_1}+a_1^2\right)$$

The population biomass in area one increases from weight gain from the growth and aging of juvenile bonefish. The population biomass is reduced as a function of the dispersal rate.

Adult Population in Area 2

$$\hat{P}_2^2 = \frac{1}{\mu_2^2}\left(\frac{E_2^2\hat{N}_2}{K_{N_2}^2+\hat{N}_2}+\delta_1^2\right)$$

The population biomass in area two increases because of weight gain from the growth and dispersal of bonefish from area one. The population biomass is reduced as a function of the natural mortality.

Model Interpretation and Application

- This model assumes that the pharmaceuticals do not affect the life parameters of bonefish because the effect of pharmaceutical contaminants on these parameters remains unknown.
- It has been demonstrated in laboratory experiments that different types of pharmaceuticals have different effects on fish species at concentrations that are similar to those in the environment (Klaminder 2019, Steinbach 2014).
- With further research, this model can be readily adapted to include the effect of pharmaceuticals on the parameters by allowing a dependency of parameters on the chemical load
- Other models that include a dependency of parameters on a chemical have been derived to study the effect of bioaccumulation of methylmercury on predator prey dynamics with rainbow trout (Huang et al 2015).

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