Systems-NET Immersive Secondment:

Joseph James Abram

Investigating the System Dynamics and Species Dispersal of Freshwater Ecosystems within the State of Florida, USA.

Investigating System Dynamics and Species Dispersal within Marine Ecosystems of the State of Florida USA.

I would like to take this opportunity to thank Systems-NET for this great opportunity and hope that they are able to provide many future researchers with similar opportunities on other Immersive Secondments.

Introduction

My Immersive Secondment took place at Harbor Branch Oceanographic Institute (HBOI) at Florida Atlantic University. Harbor Branch is a research institute of approximately 150 Ph.D. scientists focused on Ocean Science. Their work includes conservation, marine drug discovery, coastal and ecological observation, aquiculture, marine science education and ocean dynamics and modelling.

During my time at HBOI I had the pleasure of working with Dr. Peter McCarthy and his team of research students investigating the system dynamics, population growth and dispersal of the ciliate, *Loxodes rex* (figure 1).

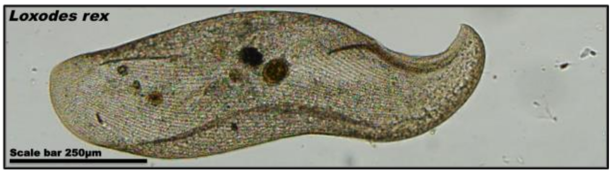

Figure 1: Loxodes rex. Image adapted from Hines et al. 2016.

Ciliates are microscopic unicellular eukaryotic organisms. They play an important role in microbial loops and form the foundations of food webs (Finlay et al 1998). The idea that ciliates can perhaps thrive wherever they find their preferred ecological niche (Fenchel and Finlay 2003) is extremely important to the understanding of global biodiversity and biogeography but in reality has proven hard to explore. Our investigation set out to examine these phenomena, and provide some theoretical explanations for dispersals that we had observed in Florida, USA. The creation of models was undertaken to form the basic underpinning by which our theories of microbial dispersal could be extended. The mechanisms surrounding long distance dispersals of microbial organisms have long been considered (Darwin 1859). The practical investigations however for this group of organisms remain sparse. By the construction of models to visualize the habitat connectivity within our study system, we can begin to understand and discuss the dispersal potential for ciliate species.

Loxodes rex is a 'flagship' ciliate species originally discovered in Tropical Africa (Dragesco 1970). The large size (over 1 millimetre), and distinctive shape of this species has made it of extreme interest to microbiologists and ecologists, despite it being only known from a few drawings and taxonomic descriptions (Dragesco and Dragesco- Kernéis 1986). This charismatic species has been traditionally used as proof for microbial endemism (Foissner 2006). The theory states that this species was so large, and so obvious that if it existed out of Africa, it would have already been documented (Foissner et al 2008). The dispersal potentials however for large flagship ciliate species are perhaps far greater than previously thought (Esteban et al 2001). By documenting *L. rex* in Florida, USA its biogeography was expanded by over 10,000km from its initial perceived restricted zone (Hines et al 2016). The implications for global biodiversity, disease dispersal, and the actual non-existence of microbial endemics can be extrapolated by this recent finding. *L. rex* is a unique but important model organism by which we can elucidate ecological insights that will have a global relevance.

The work involved system dynamic modelling and structural analysis of the freshwater habitats in which *Loxodes rex* resides and lead on to both network and agent based modelling, exploring how *Loxodes rex* has become so successful in its colonization of Florida's freshwater bodies.

Aims and objectives of the Secondment:

1) *To apply numerical and structural analysis techniques explored in my research to marine systems of the Florida coast.*
   - I was able to use system dynamic modelling techniques to help the team investigate the dynamic structure of *Loxodes rex's* habitat and provide a new perspective, into the role of the species within its environment.
2) *To collaborate with Marine Ecosystem Health research department and Ocean Dynamics and Modelling department.*
   - The main team that I worked with at HBOI were interested in how micro-organisms affect both the health of marine ecosystems and the people that use them every day. Upon arrival at the institute, I met with both Dr. Laurent Chérubin and Dr. Mingshun Jiang, members of the Ocean Dynamics and Modelling team and over the course of my Secondment, I was not only able to present my work to them but also discuss techniques used in their work and discuss potential future joint projects.
3) *To investigate the current socio-ecological practices that affect the Florida reefs, contributing to my current research focus and enhancing computational modelling skills.*
   - Attendance at the weekly "Ocean Science Lecture Series" during my time at HBOI allowed me to learn about some of the practices, both on a physical and modelling basis that are used on the Florida reefs. In terms of enhancing my computational skills, I learned to use an entirely new coding software and have now been exposed to

designing and simulating both network and agent based models, which I had little experience in prior to this project.

It is the intention of the team at HBOI to publish our collaborative work undertaken during the Immersive Secondment including the use of many of the models discussed within this report. As I do not own the Intellectual Property to all of the information within this project, some of the information and final models are not able to be shown pending publication. However, once the paper is published I will be happy to send Systems-NET a PDF of the final product and of course Systems-Net will be acknowledged for their support and funding of this project within the published paper.

The project:

This project allowed me to pull from my existing knowledge of system dynamic modelling but also gave me the opportunity to learn many new modelling techniques. It allowed me to practise explaining the benefits and limitations of using system engineering techniques to unfamiliar researchers, whilst also providing a base with which to discuss future projects with other system engineering researchers at HBOI. The following sections provide an overview of the work conducted during the Immersive Secondment.

The project began by using system dynamics to investigate the freshwater bodies of Florida and building a structural representation of the drivers which affect the survival of *Loxodes rex.* The project then moved onto studying the ability for *Loxodes rex* to successfully colonise a single water body and finally, investigating the properties of a system which would allow the species to successfully spread across the entire State of Florida.

Building a cyclic diagram and System Dynamic Model.

At the beginning of the project, a cyclic diagram was constructed to begin to understand the complex nature of interactions and feedback processes which affect the success of *Loxodes rex* to populate its environment (Figure 2).

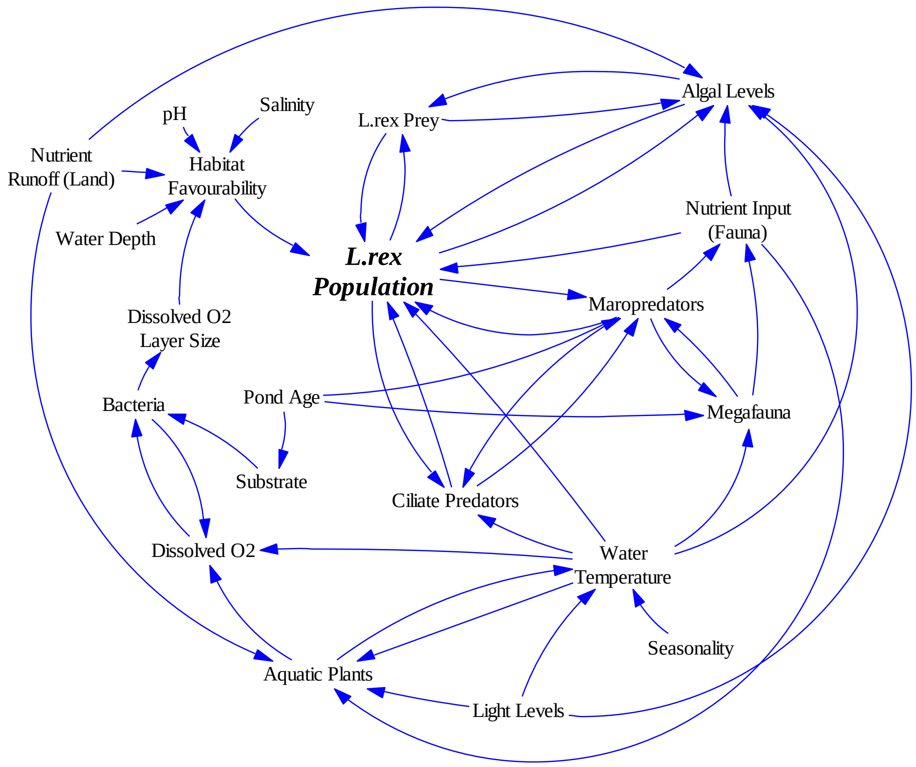

Figure 2: Cyclic diagram containing the main driving factors affecting a population of Loxodes rex within a single waterbody.

This provided the group with a visual output of system interactions, consolidating all of their knowledge of the system into one simple diagram. This provided an excellent base and reference point to go back to during any discussion within the project that could be easily adapted and adjusted as the project developed.

In order to begin investigating the structural properties of this system, it was converted into a system dynamics model (Figure 3). This model had significance not only in investigating the systems feedback mechanisms present, but was also designed to be able to conduct sensitivity analysis and structural loop dominance analysis on the system drivers pending more data at a later stage. These techniques would be used to identify dominant structures of the ecosystem at critical times during the growth and colonization by *Loxodes rex.*

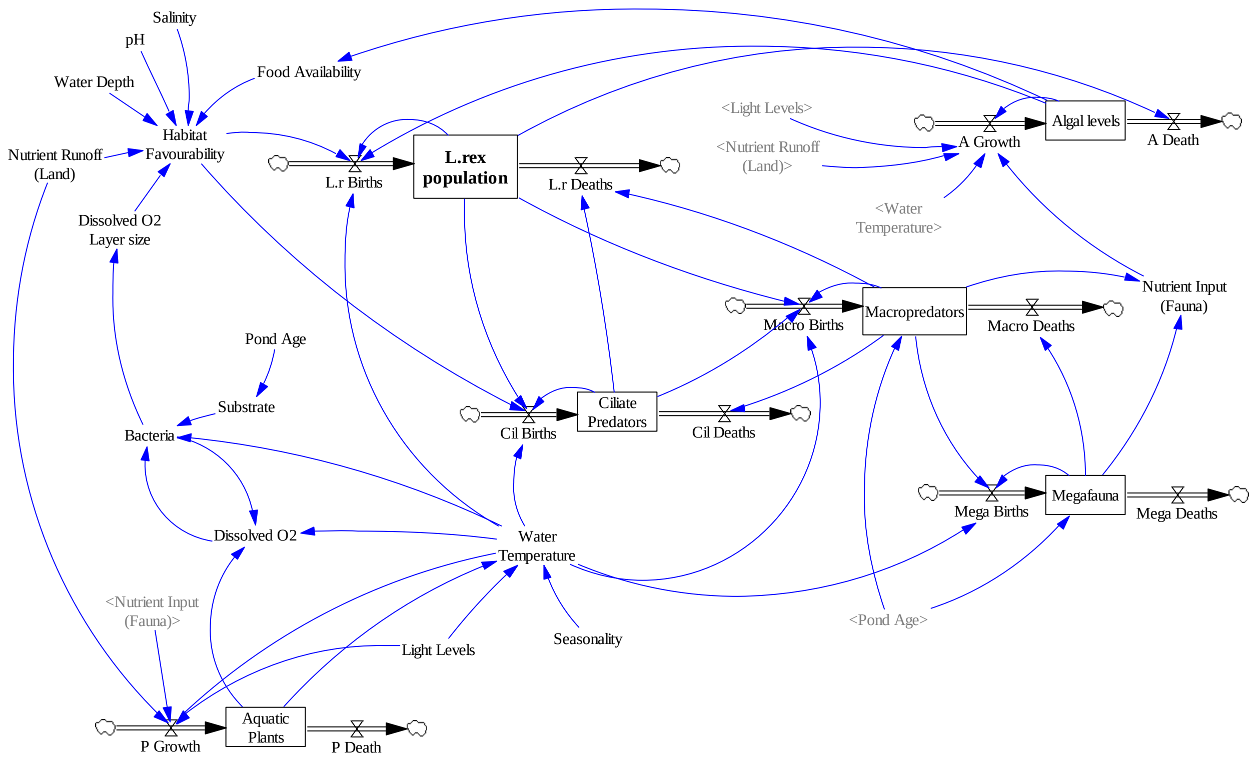

Figure 3: System dynamics diagram of the system drivers and interactions affecting Loxodes rex within its local freshwater environment.

Structural analysis was conducted on the system dynamics model, which found that there were 25 independent feedback loops within the system. This analysis was undertaken using Oliva's 'structural analysis' software (Oliva 2004) and the loops were identified using the shortest independent loop method (SILS) as described in Kampmann (1996) and Oliva (2004). Feedback loops act as key drivers in system behaviour; it is important to acknowledge their presence and influence when attempting to understand transitions in system states (Kampmann & Oliva 2006). The adjacency matrix and reachability matrix can also be seen in figures 4, a & b respectively, where the axis represent the number of variables in the model and 'nz' is the number of connections found within the structure.

Despite limited data being available for all system components, the team found that the system dynamics approach provided a new perspective for thinking about the system's main properties and interactions that they had not been exposed to prior to the project.

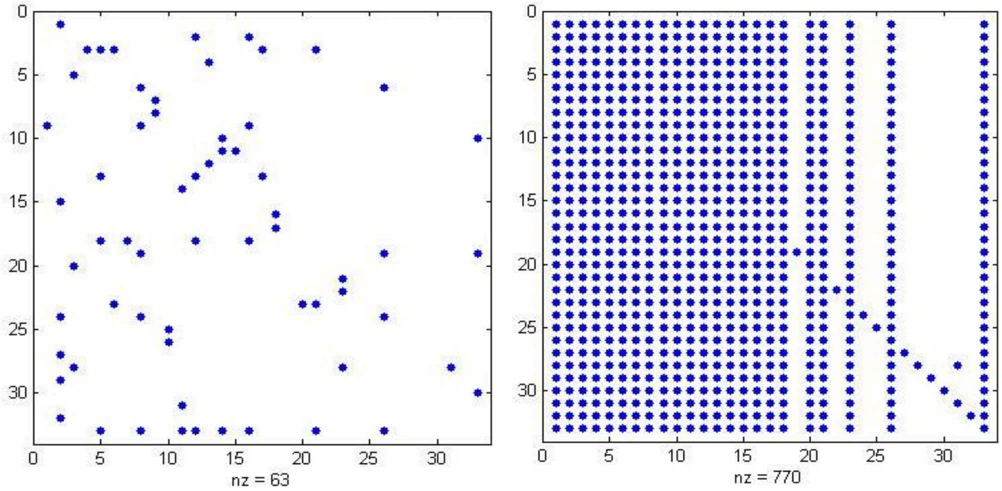

Figure 4 a & b. a) adjacency matrix of the variables within the Loxodes rex system dynamics model. 4 b) reachability matrix of the variables within the Loxodes rex system dynamics model. Axis represent the number of variables in the model and 'nz' is the number of connections found within the structure.

Identifying the Capability of the Loxodes rex to inhabit its local surroundings

During the Immersive secondment, laboratory experiments were undertaken by members of Dr. McCarthy's team to identify doubling times of *Loxodes rex.* The purpose of this was to identify, under ideal conditions, how long it would take the species to colonise a single waterbody up to its carrying capacity.

Using this data and some simple calculations, I was able to show the team that even with extremely high death rates (up to 80%), the species could still reach numbers close to carrying capacity within a matter of months.

Dispersal models

In order to investigate the parameters affecting the dispersal of *Loxodes rex* across the state of Florida, two conceptual models were followed which allowed the user to construct multiple scenarios with which to investigate properties such as habitat connectivity, initial seeding of the species, spreading capability and colonisation success. Dispersal was visualised as the spreading of the species across a network, whereby each node represented a freshwater body of Florida capable of housing the species and links between nodes were means by which the species would disperse.

It is generally unknown exactly how the species has been able to disperse, theories include via bird flight (as water and sediment get trapped on birds' feet, feathers and bills), storm events, strong winds, water pathways and land animals.

The main use of computational modelling for the project was to investigate the significance between habitat connectivity and initial seeding of the species. The models were also designed to accommodate for future experimentation and expansion, if other theories came to light.

The outputs of the models combined with growth experiments from the lab were used to infer relative times for the spread of the species (i.e. months vs. years vs. decades to spread).

The "Neighbours Dispersal" model.

The "Neighbours Dispersal" model (Figure 5) was built as a proxy for the dispersal of *Loxodes rex* within the State of Florida. The freshwater bodies of Florida, capable of being colonised by the species were represented as nodes on a network, whose connections represent any possible means of transport by which the species could spread (bird flight, storms, water pathways, mammals etc.). Each waterbody had three potential states during simulation:

- Clear (light blue circle): The waterbody does not have any of the species present.
- Exposed (yellow circle): The waterbody has been exposed to one or more of the organism. The waterbody is now able to reject the species (waterbody converts back to clear), or accept the species (waterbody converts to inhabited)
- Inhabited (Red *Loxodes rex* shape): The species was able to successfully colonize this waterbody.

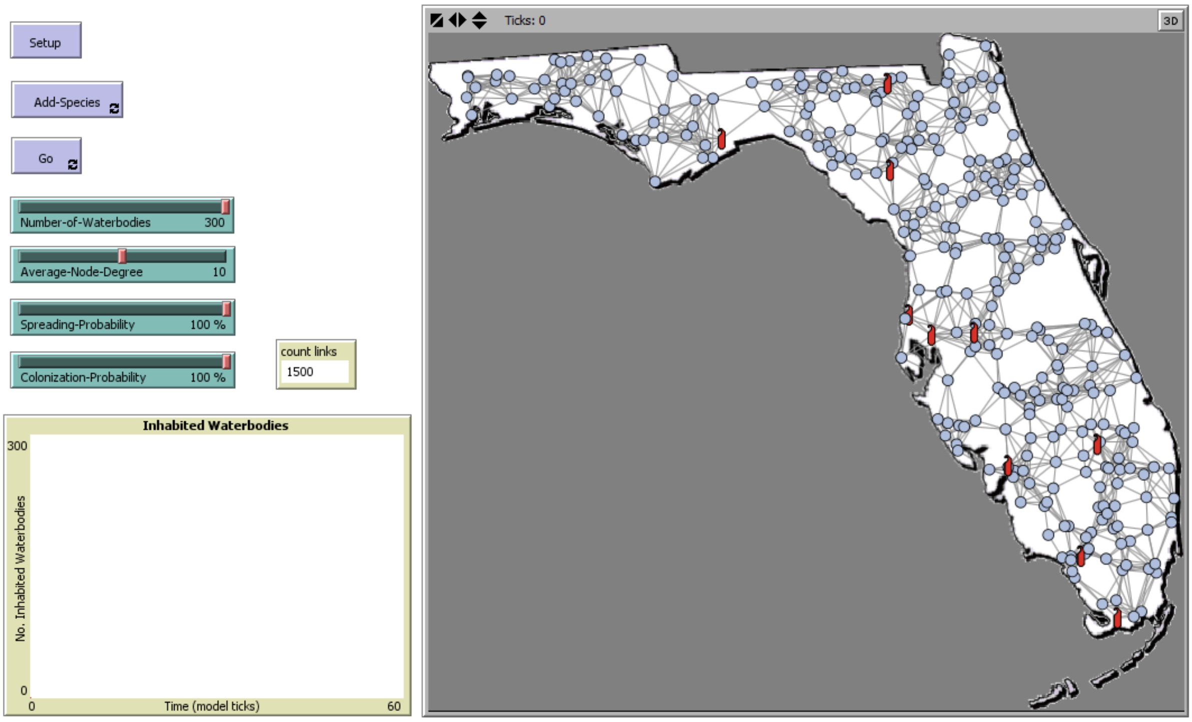

Figure 5:The Neighbours Dispersal Model. Clear waterbodies are represented by blue circles. Exposed waterbodies are yellow circles. Inhabited waterbodies are red and in the shape of Loxodes rex.

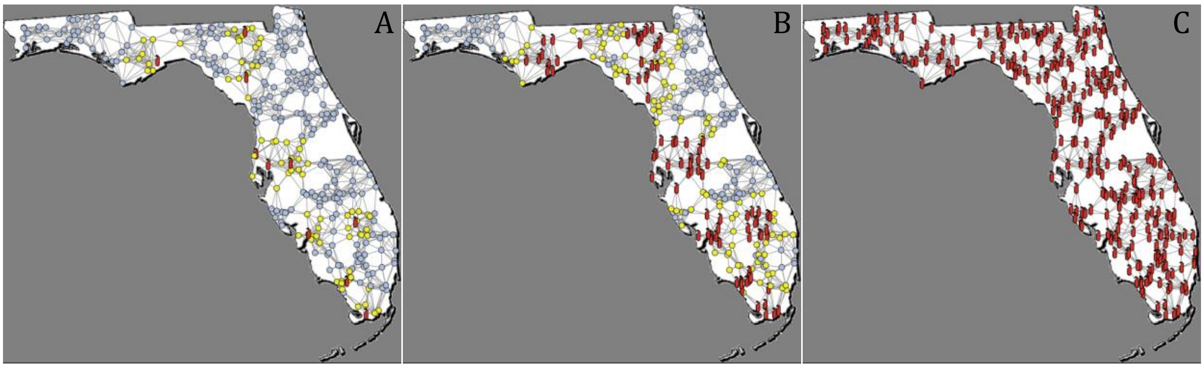

Figure 6: A, B & C. A, B & C shows a single scenario of the neighbours model captured at three points in time.. A: 1 tick, B 2 ticks, C 6 ticks (final)

The user was able to set the following parameters: the number of waterbodies which the species could spread to; the initial number of inhabited waterbodies; the connectivity of the network; the probability of successful spreading events and the probability of successful colonization events occurring. The chance for spreading and colonization events to occur were set homogeneously across the network.

The spread of the species within the state of Florida (Figure 6) is comparable to how a virus might spread across a human population. Both can be visualized as networks within which dispersal events operate. The ability for the species to then dominate the network is determined by both biological properties of the nodes, but also structural properties of the network.

The "Bird Dispersal" Model

The "Bird Dispersal" model (Figure 7) represents an alternative method of dispersal, whereby successful spreading events are assumed to be caused only via bird flight. Similar to the Neighbours model, dispersal between waterbodies is assumed to act on a network structure, whereby each node represents a freshwater body capable of housing the species. In the Bird model however, connections between nodes represent bird flight paths, which bird agents are able to path over. Waterbodies are capable of being in one of the same three states, (Clear, Exposed and Inhabited), as the neighbours model.

In the event that an agent successfully flies between an inhabited waterbody and a clear waterbody, a successful spreading event occurs, causing the waterbody to become exposed to the species. The chance that a spreading event will result in a successful colonization is determined by the user. An example of the spread can be seen in figure 8 a, b and c.

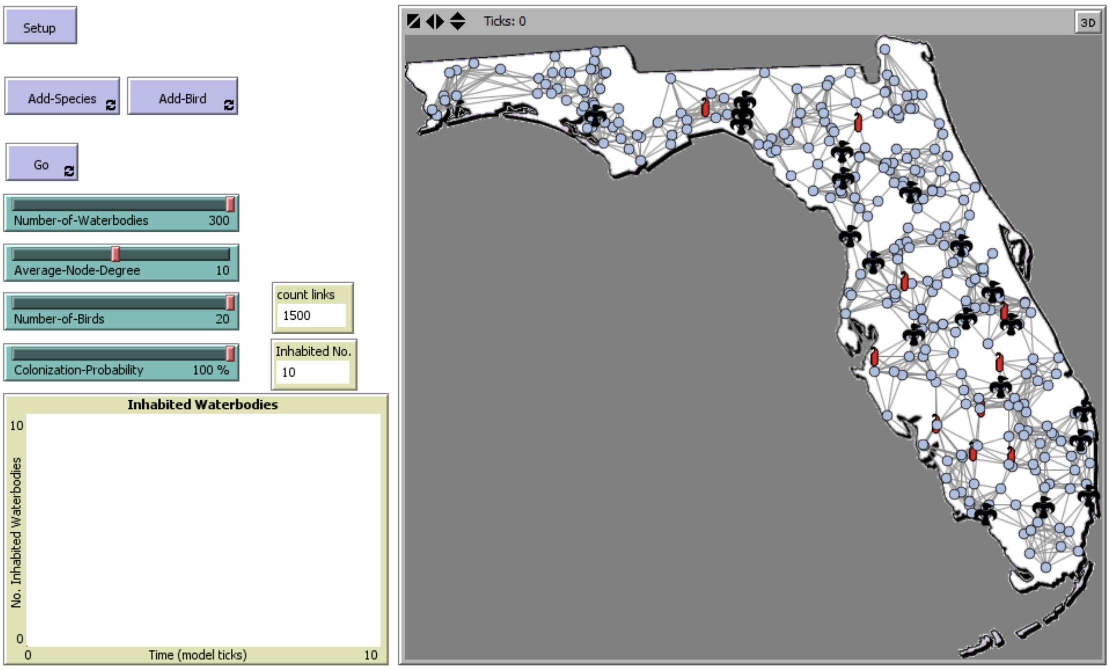

Figure 7: The Bird Model. Clear waterbodies are represented by blue circles. Exposed waterbodies are yellow circles. Inhabited waterbodies are red and in the shape of Loxodes rex. Birds (black bird shapes) are able to path across the network spreading the species.

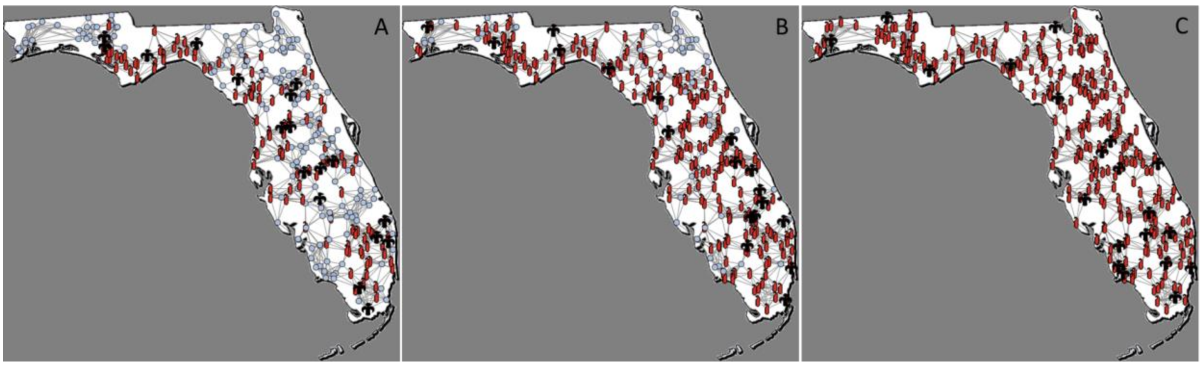

Figure 8, A, B & C shows a single scenario of the bird model captured at three points in time. A = 25 model ticks, B = 50 model ticks, C = 323 model ticks.

The user is also able to set the following parameters: number of waterbodies present; connectivity; number of bird agents present (representing number of potential successful spreading events per time step) and the probability of a successful colonization occurring.

In the bird model, the ability for the species to spread is controlled not only by the biological factors of the waterbodies and structural factors of network but also the random movements of the birds throughout the network. The biggest thing to notice is that the bird model takes much longer for the species to fully occupy every waterbody as they are relying on the random pathing of agents, as much as the state of the neighbouring nodes.

Model Purpose and Discussion

The main interest of the team was looking at how long it would take for *Loxodes rex* to successfully spread across the state of Florida. By successfully spreading, it was meant that, if anyone were to sample in a waterbody within the state that had the correct conditions to house the species, they would be able to find it. To aid the investigation, the Neighbours and Bird model were used as platforms to discuss how connectivity and initial seeding of the species could affect its ability to spread.

Nine scenarios were generated from each model in which different levels of connectivity vs different seeding events were generated. During simulations, properties investigated include: the time taken for successful dispersal; the trend of the spread (i.e. linear vs. step vs. exponential etc.) and whether the dispersal could successfully colonize all of Florida. In some cases during low connectivity, the networks were not always fully connected, leaving 'islands' of clear waterbodies where sampling events would retain null results (see Figure 9).

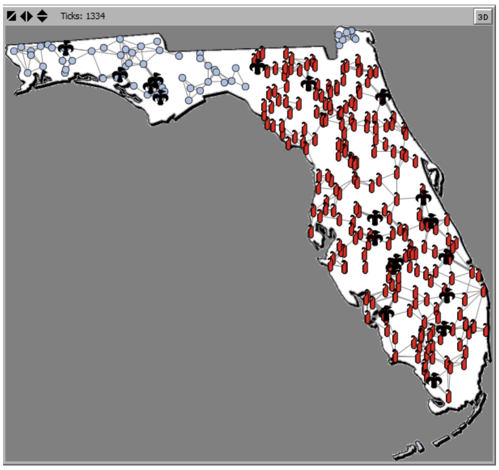

Figure 9: Showing the Bird Dispersal model, where network 'islands' limiting the spread of Loxodes rex.

It is the intent of the team at HBOI to use these models as both platforms and visual aids to reinforce their discussions on limitations of spreading events and drivers of spreading events.

How this project could be extended:

More data could prove extremely useful in understanding this system better. Not only could the models be made more accurate to represent dispersal trends but also further structural analysis could be run on the systems dynamics model in order to determine the most influential drivers of the freshwater systems, which are allowing this species to thrive. Unfortunately collection of this sort of data is an extremely lengthy process and sometimes may be impractical to obtain. In light of this, all models have been constructed to be easily adapted in the future with the system dynamics able to take and process field data as soon as it becomes available.

Model Limitations

Limitations include only creating a network across the state of Florida and therefore the network is limited by the state boundaries.

Dispersal within the bird model is limited by the amount of birds allowed to fly across the network. Each bird representing a single successful transmission pending the flight occurs between an inhabited and clear state waterbody.

Spreading probability and colonisation probability are set homogeneously across the entire network. While unrealistic, it was discussed by the team that using these general conditions, it is simple to represent seasonal variation and both spreading and colonisation success chance would be much higher in the summer than winter months.

How a Systems Engineering approach has benefitted the research at Harbor Branch

The work undertaken during the Immersive Secondment is intended to be integrated into the current thesis work and potential publications of research students at Harbor Branch.

Alongside this, the team have expressed their interests in using many of the computer models created during the secondment as part of their teaching and lecture series. Members of the team have also requested for the models to be used as part of oral and poster presentations to be taken to conferences worldwide and have requested that I come along to some of them to benefit model discussion, purpose and techniques.

In order to help the team further, I took some time to create an agent based model which represents how their species acts in a laboratory environment. This took very little time out of my work schedule, but was well received and appreciated by the HBOI team. This model is now intended to be used during lectures and presentations to explain behaviours of their species.

The model, entitled "The Bottle Model" portrays how *Loxodes rex* acts when confined to a 500 mL sample bottle within the laboratory. By assigning a simple set of rules for each agent to follow, the behaviour of the species can be easily replicated.

Figure 10 shows the bottle model where three layers have formed: oxygenated (light blue with red *Loxodes rex*), 5-10% oxygen (dark blue with yellow *Loxodes rex*) and the Anoxic layer (black with orange *Loxodes rex*). The change in colour of Loxodes rex is purely for visual aid as their colour is not determined by their environment in this way. Predators can be seen swimming around in the highly oxygenated zone, but are not capable of surviving at the lower oxygen levels and so remain in the light blue zone.

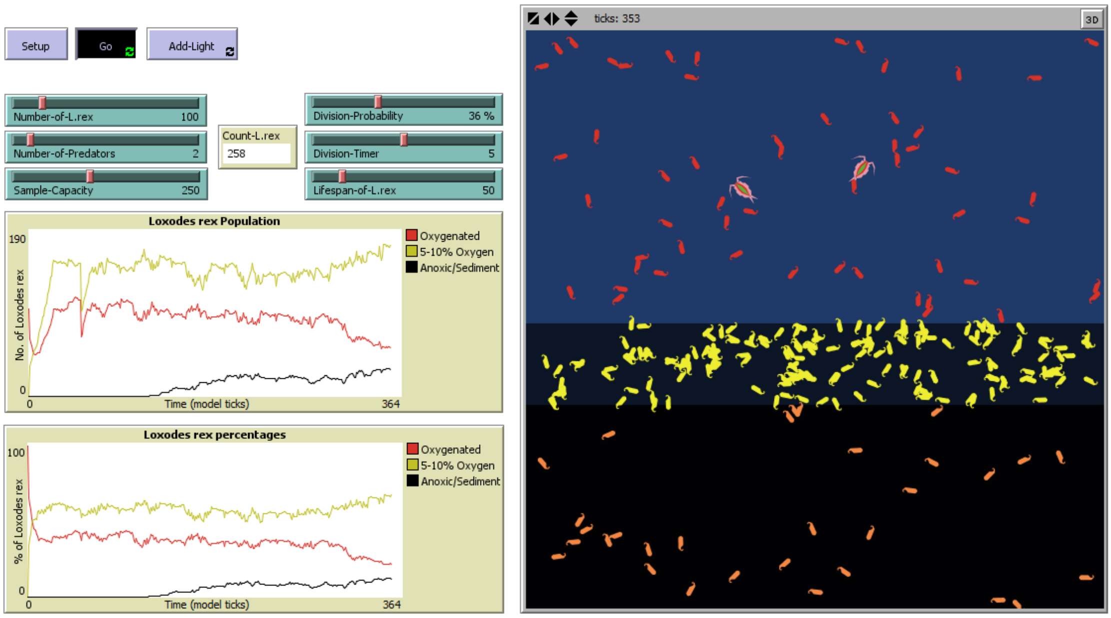

Figure 10: The bottle model: showing the behaviour of Loxodes rex within a 500ml bottle of the laboratory. The zones include oxygenated (light blue with red Loxodes rex*), 5-10% oxygen (dark blue with yellow* Loxodes rex*) and the Anoxic layer (black with orange* Loxodes rex*). Predators (pink) will only stay within the oxygenated zone leaving a safe zone for Loxodes rex to thrive.*

The model was designed to show how *Loxodes rex* tend to cluster within the 5-10% oxygenated zones and how this can be achieved through a very simple set of rules. In reality the movements of *Loxodes rex* are reaction based and are not made through conscious decision making. By assigning a simple set of rules to each agent, their movements and behaviour patterns could be replicated with relative ease.

Features within the model included: Initial number of *Loxodes rex*; Initial number of predators; predator prey interactions; cell division of *Loxodes rex*; varying division times and carrying capacity of the bottle. At a later stage a light feature was added (Figure 11) whereby the user could place a light source anywhere within the bottle. *Loxodes rex* prefer dark and slightly oxygen depleted conditions and so were programmed to avoid any light source they came into contact with (shown by black Loxodes), thus creating an avoidance zone where *Loxodes rex* would not enter.

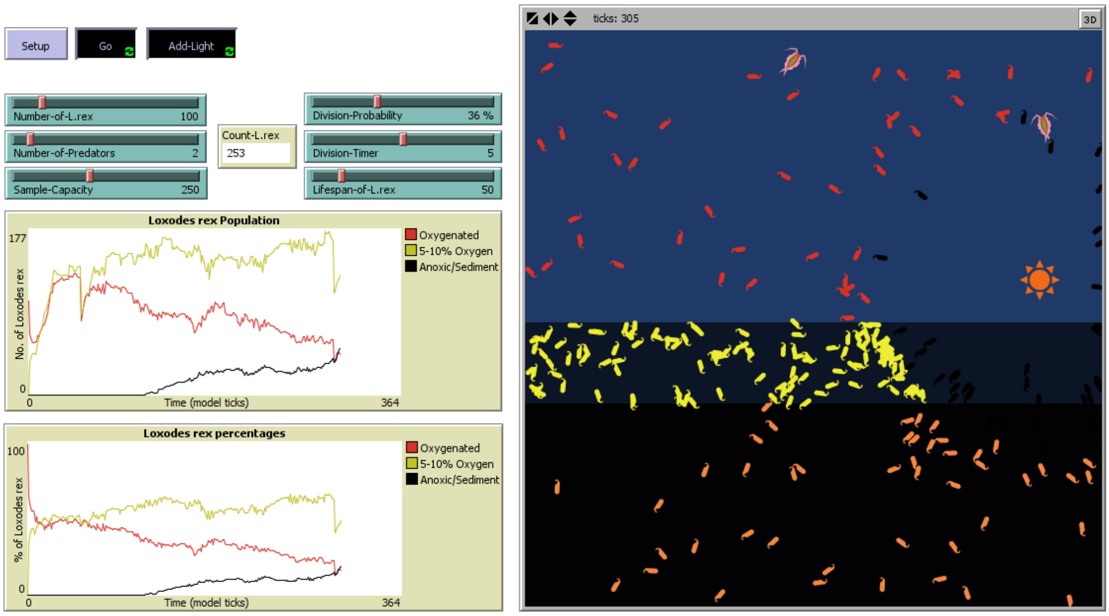

Figure 11: The Bottle model: showing the input of a light source (orange sun) causing the Loxodes rex to move away into more preferable conditions.

How the work at Harbor Branch has benefitted my project work and benefitted my CV

I have added to my academic skill set including learning to code network and agent based models. This included an introduction to a new software, Netlogo (Wilensky 1999).

I was able to use system dynamics as a bridge between the work that I do for my PhD and a team who have very limited experience in using modelling to aid their research. This gave me plenty of opportunities to explain the benefits of incorporating a system dynamics approach to project work, while still grounding what expectations we must have of using modelling.

Specific to the research within my Ph.D. the ciliate *Loxodes rex* represents an enormous flow of energy and nutrients transfer through a system. It is thought to be one of the top predator species within its ecological niche, and can contribute to a greater biomass than other larger creatures within lake systems, including fish. However, no-one realized this species was even present in Florida, or the Americas until recently (Hines et al 2016). My work which involves investigating system drivers and causal effects on system behaviour will greatly benefit from a discussion of our capabilities of structurally modelling and analysing a system when there are highly influential components we are not even aware are present.

Opportunities undertaken during the Secondment:

- Weekly opportunities to present research during group meetings and while visiting professors across the university.

- Opportunities to work with Dr. Peter McCarthy and his team.
- Numerous contacts with other student researchers who I worked alongside and who I presented to and saw presentations from.
- Weekly seminars attended including:
  1) Dr. Megan Davis: *Ocean Entrée with a twist: Shrimp Culture and Culinary Showcase*
  2) Dr. Laurent Chérubin: *Frontal, Wake Eddy, Topology Control and Ecological Constraints of Fish Spawning Habitat*
  3) Dr. Jan Rines: *Exploring the Dazzling Diversity of Microscopic Life in the Sea*
  4) Dr. Amy Wright: *Cures for Malaria, Tuberculosis, Alzheimer's. An Update Natural Products Discovery at HBOI*

Future Opportunities

Presenting work to Prof. Mingshun led to a discussion of potential future projects, including that of a post-doc pending funding availability nearer the end of my PhD. The project would conduct work on the Indian River Lagoon from a system dynamics perspective, investigating the drivers which have been affecting its recent regime shifts into alternative eutrophic states.

How has systems engineering benefited from the overall development of this project?

This type of project not only gave experience to someone from Systems Engineering and modelling background to relate his work to a non-systems engineering audience, it also showed a group of researchers who are purely field and lab based the advantages that a systems engineering approach could bring to their research. So overall it built bridges between scientific disciplines.

More specifically the work conducted is now intended to be used as part of presentations and potentially incorporated into teaching lectures, bringing systems engineering to audiences which may never have been exposed to it before, particularly in undergraduate studies.

Extra-curricular activities during weekends

Dolphin Day

Gatorland

Florida Keys

Miami Beach

Works Cited:

Darwin, C., 1859. On the origin of species by means of natural selection. John Murray, London.

Dragesco, J., 1970. Ciliés libres du Cameroun. Ann Fac Sci Yaoundé (Hors série): 1–141.

Dragesco, J., Dragesco-Kernéis, A., 1986. Ciliés libres de l'Afrique intertropicale. Introduction à la connaissance et à l'étude des Ciliés. Editions de l'Orstom Faune Tropical XXVI, Paris. ISBN 2-7099-0750-X

Esteban, G.F., Finlay, B.J., Charubhun, B., Charubhun, N., 2001. On the geographic distribution of *Loxodes rex* (Protozoa, Ciliophora) and other alleged endemic species of ciliates. J Zoology 255:139–143. doi :10.1017/S0952836901001200

Fenchel, T., Finlay, B.J., 2003. Is microbial diversity fundamentally different from biodiversity of larger animals and plants? Eur J Protistol 39:486–490. doi:10.1078/0932-4739-00025

Finlay, B.J., Esteban, G.F., Fenchel, T., 1998. Protozoan diversity: converging estimates of the global number of free-living ciliate species. Protist 149:29–37. doi:10.1016/S1434 4610(98)70007-0

Foissner, W., 2006. Biogeography and dispersal of micro-organisms: a review emphasizing protists. Acta Protozool 45:111–136

Foissner, W., Chao, A., Katz, L., 2008. Diversity and geographic distributions of ciliates (Protista: Ciliophora). Biodiver Conserv 17: 345–363. doi:10.1007/s10531-007-9254-7

Hines, H.N., McCarthy, P.J., Esteban, G.F., 2016. The first record for the Americas of *Loxodes rex*, a flagship ciliate with an alleged restricted biogeography. Microbial Ecology. 71: 5-8. doi: 10.1007/s00248-015-0656-x

Kampmann, C.E., 1996. Feedback loop gains and system behavior (unpublished manuscript). In Proceedings of the Int. System Dynamics Conference. System Dynamics Society: Cambridge, MA; 260–263 (summarized).

Kampmann, C.E., Oliva, R., 2006. Loop eigenvalue elasticity analysis: three case studies. System Dynamics Review 22 (2): 146–162.

Oliva, R., 2004. Model structure analysis through graph theory: partition heuristics and feedback structure decomposition. System Dynamics Review 20 (4): 313– 336.

Wilensky, U., 1999. NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL.