Ph.D. Advancement

Formalisms for ecological applications

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Population Ecology

Naturalists and biologists need to model and simulate large populations of interactive animals.

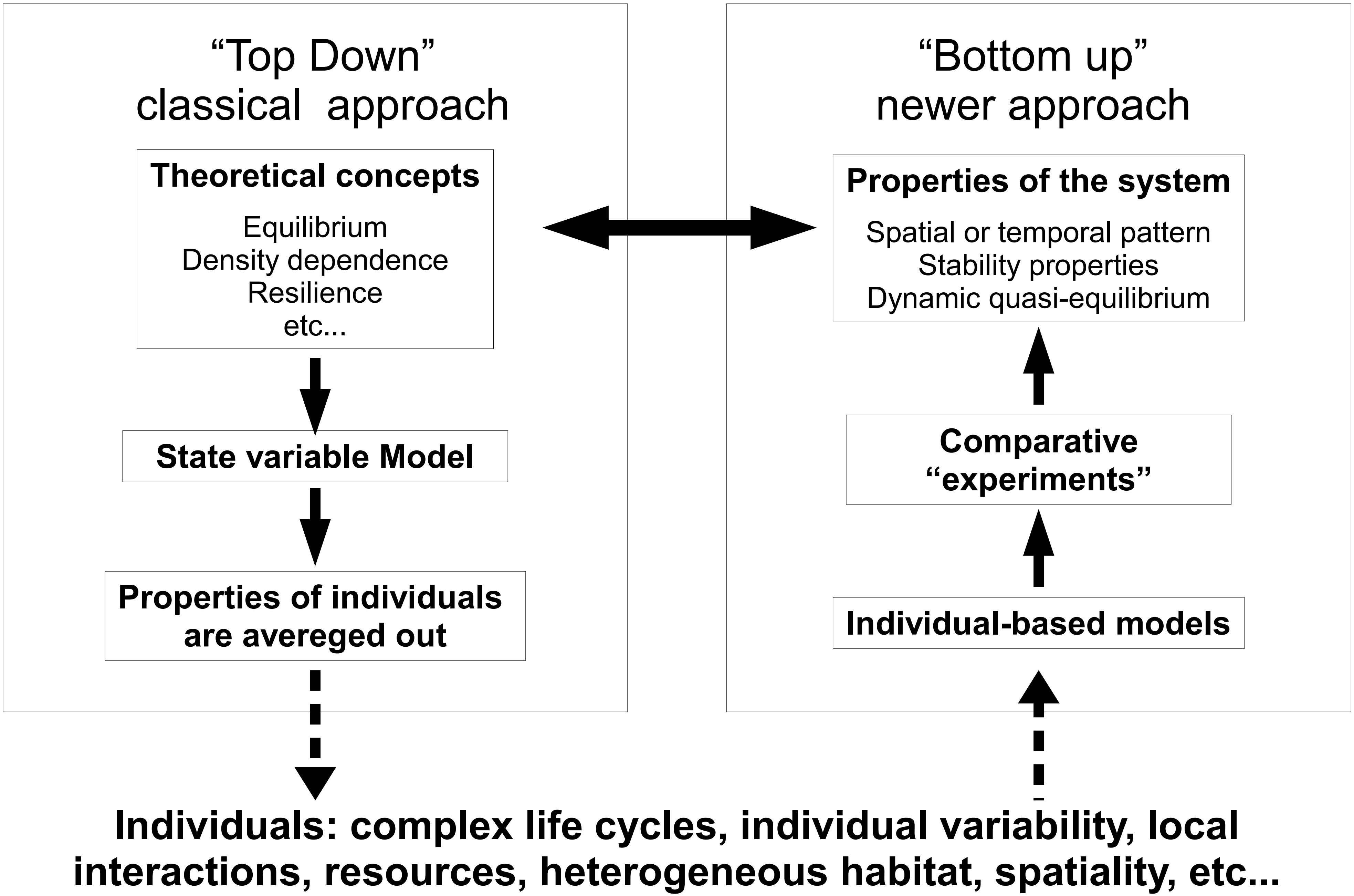
Two possible roads

- classical: differential equations
- modern: individual-based models

Motivation matters:

Pragmatic: use the model as a tool	vs	Paradigmatic: search for the overall meaning and the theory

Approaches in ecological modelling



Classical approach

- No reference to behavior
- Everything is reduced to population growth

Successful in devising and demonstrating concepts such as density dependence and intra- and inter-specific competition.

Limited success in being predictive: they can produce understanding of the observations but the predictions are not testable

Individual-based models

PROS	CONS
Can determine what individual properties and what elements are essential to the overall population dynamics.	Difficulties in the determine the right resolution and to have the same one in the whole model.
Can include spatial dynamics and abiotic factors.	Only partial knowledge is available at small resolutions
Supposedly more testable as closer to reality.	But closer to reality means more parameters which in turn means more effort to determine them.

Moreover, the search for the theory behind the model is more difficult since overall properties must emerge (and be recognized) from the details.

Case Study: *Emys orbicularis*

E. orbicularis is a freshwater european turtle with a wide western distribution, from Portugal to Kazakhstan, from Denmark to southern Italy.

The European pond turtle is inserted into the Habitat Directive (EU) and is classified as "near threatened".

Yet, it suffers from inadequate protection and management rules mostly because comparative approaches on different populations are still scarce.

Modelling the problem: Syntax

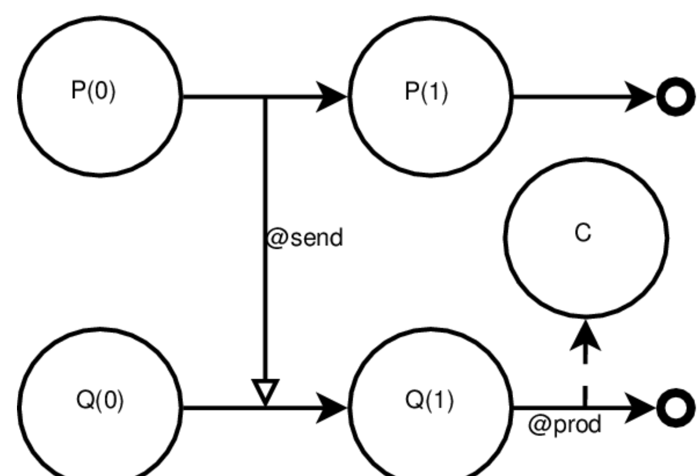
Automata with distinct names

$$A \quad ::= \quad \langle n \in \text{Names} \; , \; \text{STATES} \; , \; i \in \text{STATES} \; , \; F \subseteq \text{STATES} \; , \; \text{TABLE} \rangle$$

$$\text{TABLE} \subseteq \text{STATES} \times \text{TRANS} \times (\text{STATES} \cup \text{Nil})$$

$$\begin{aligned} \text{TRANS} \quad ::= \quad & @r \mid \downarrow n@r \mid \uparrow n@r \\ & \mid \text{consume}(n)@r \mid \text{emit}(n)@r \\ & \mid !A(\text{new}())@r \end{aligned}$$

with $n \in$ Names,
$r \in \mathcal{R}^+$
and new() returns a fresh name from Names



Name Convention

The set of Names used can be any infinite set of distinct strings.

For ease of understanding and of modelling, I'm using a hierarchical structure for names, intended to mimic the standard species classification (Species, Genus, etc...) whose semantics is the following:

$$\text{Names} = \{n_1.n_2.\cdots.n_m \mid m > 0, n_i \in N_i\}$$

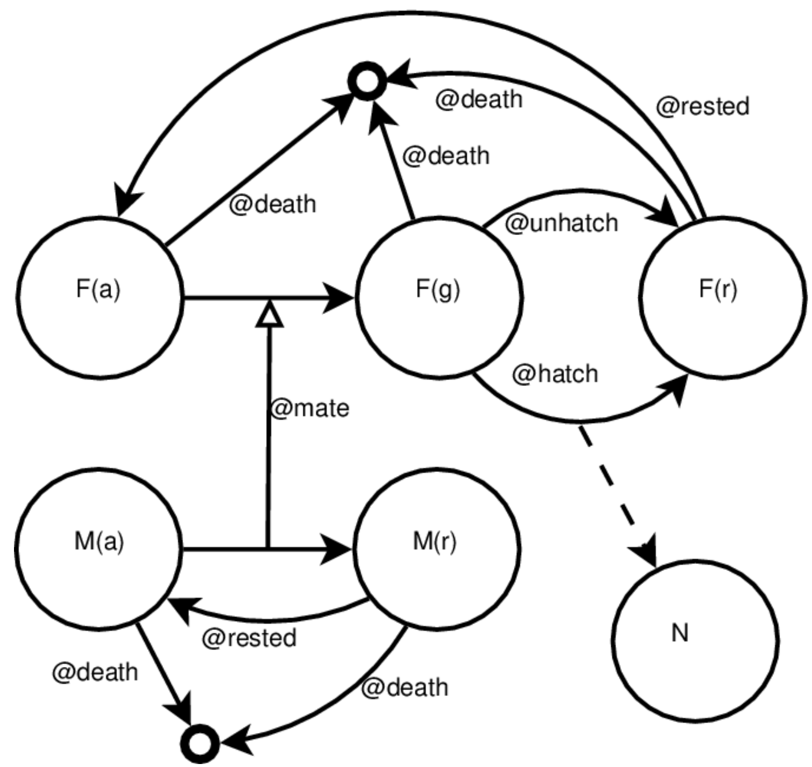
with N_i = distinct strings $\cup$ '-' ('don't care' symbol)

and where $N_i \cap N_j = \{\text{'-'}\}$, $\forall i, j$

Example: *E. orbicularis* Reproduction Cycle

$$F = \begin{cases} id.\text{female.turtle}, \{F_a, F_g, F_r\} \\ \langle F_a, \text{@death}, Nil \rangle \\ \langle F_a, \downarrow \text{-.male.turtle@mate}, F_g \rangle \\ \langle F_g, \text{@death}, Nil \rangle \\ \langle F_g, \text{@unhatch}, F_r \rangle \\ \langle F_g, !N(\text{new().nest@hatch}), F_r \rangle \\ \langle F_r, \text{@death}, Nil \rangle \\ \langle F_r, \text{@rested}, F_a \rangle \end{cases}$$

$$M = \begin{cases} id.\text{male.turtle}, \{M_a, M_r, Nil\} \\ \langle M_a, \text{@death}, Nil \rangle \\ \langle M_a, \uparrow \text{-.female.turtle@mate}, M_r \rangle \\ \langle M_r, \text{@death}, Nil \rangle \\ \langle M_r, \text{@rested}, M_a \rangle \end{cases}$$



Case Study:
Tropheus moorii (tropical cichlid)

These little colored fishes, natives of african central lakes (lake Tanganyika) with over 40 different morphs distributed throughout the lake.

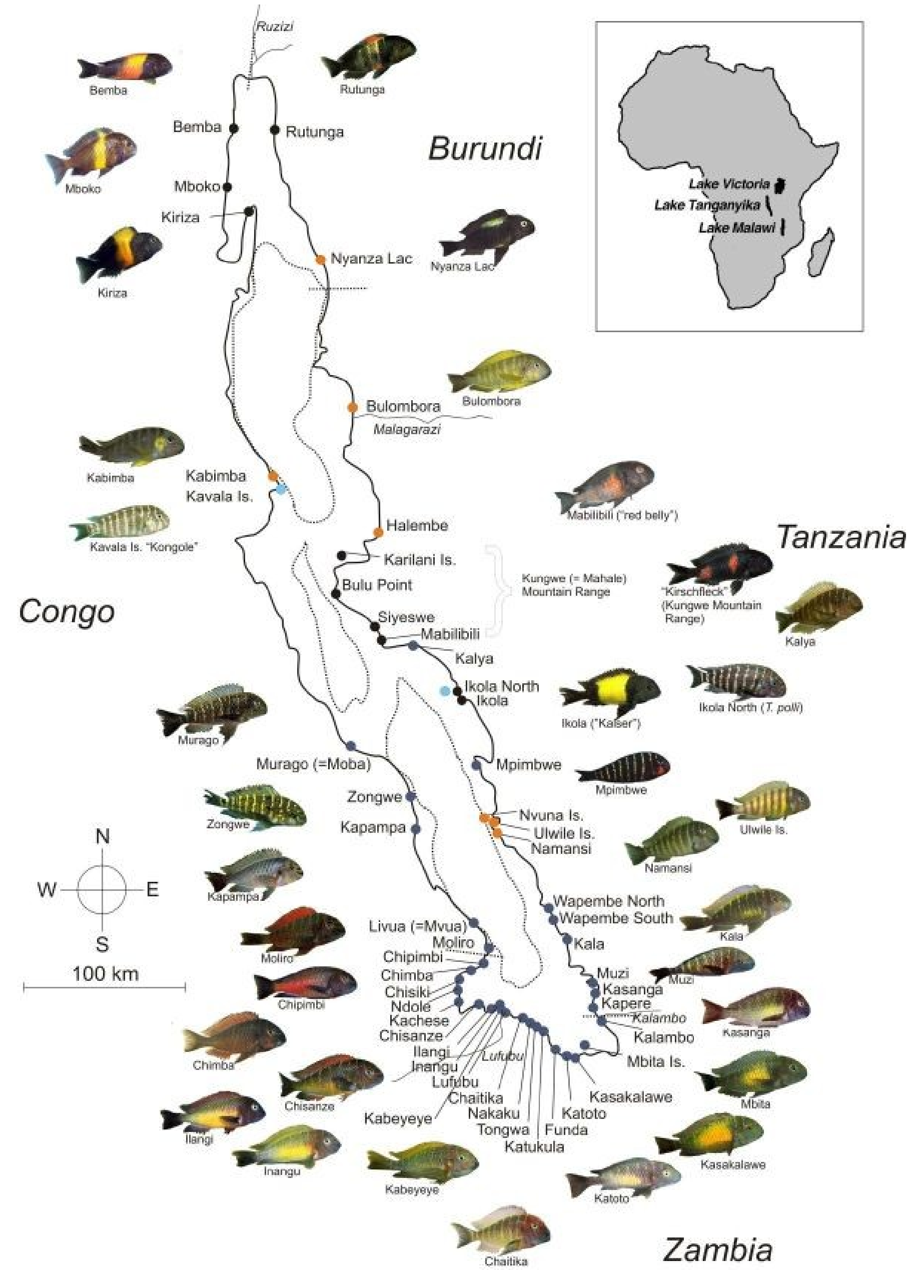
This form of peripatric speciation (speciation with loosely interconnected habitats) is quite difficult to explain given the existing models.

Cyclid in Lake Tanganyika

Fishes that lives in nearby communities have different colors.

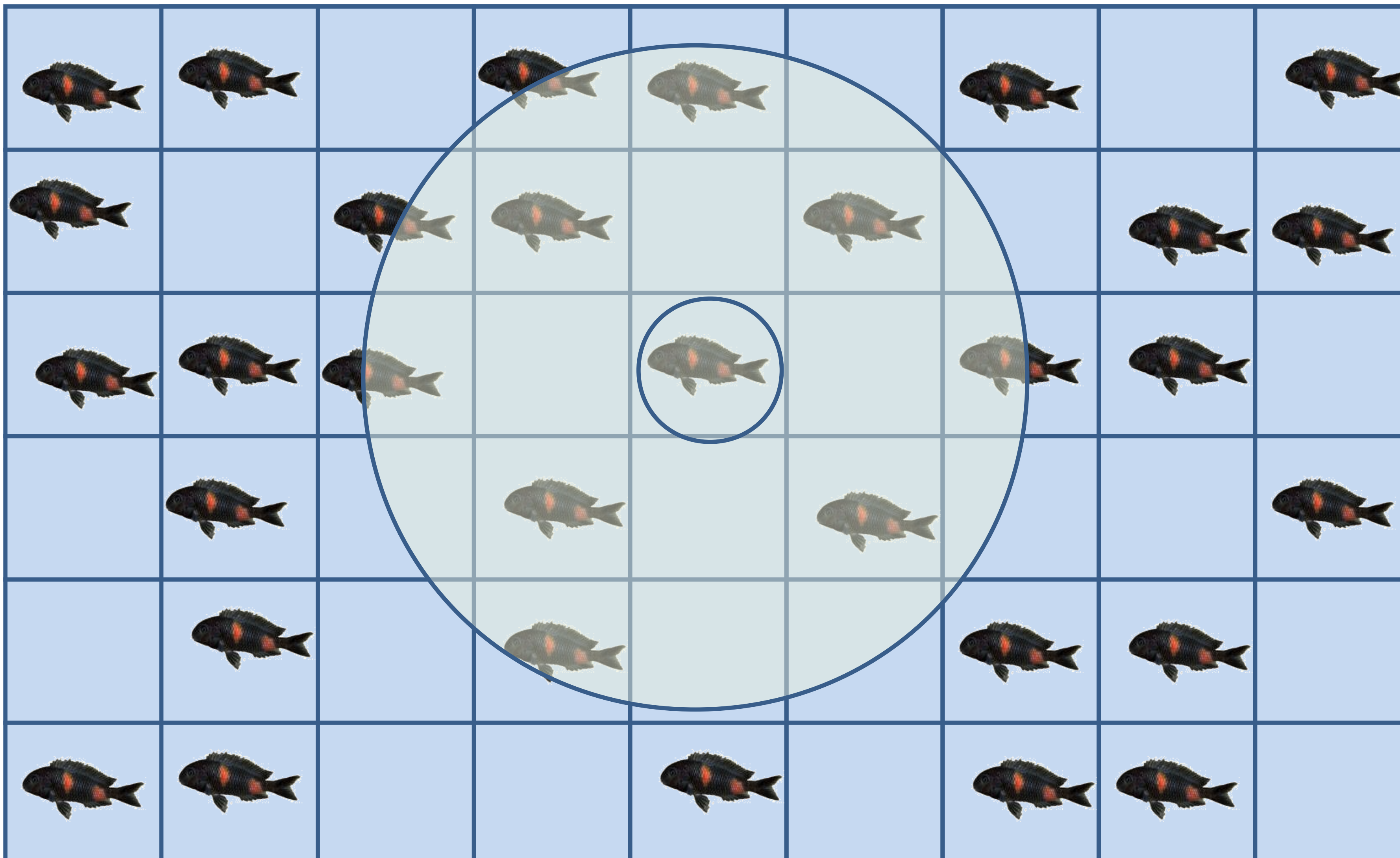
There are color morphs (i.e. *T. polli* and *T. moorii Bulu Point*) that live along the same coast line but at different depth.

Question: is ecological trait differentiation enough to induce morph separation through sexual selection?



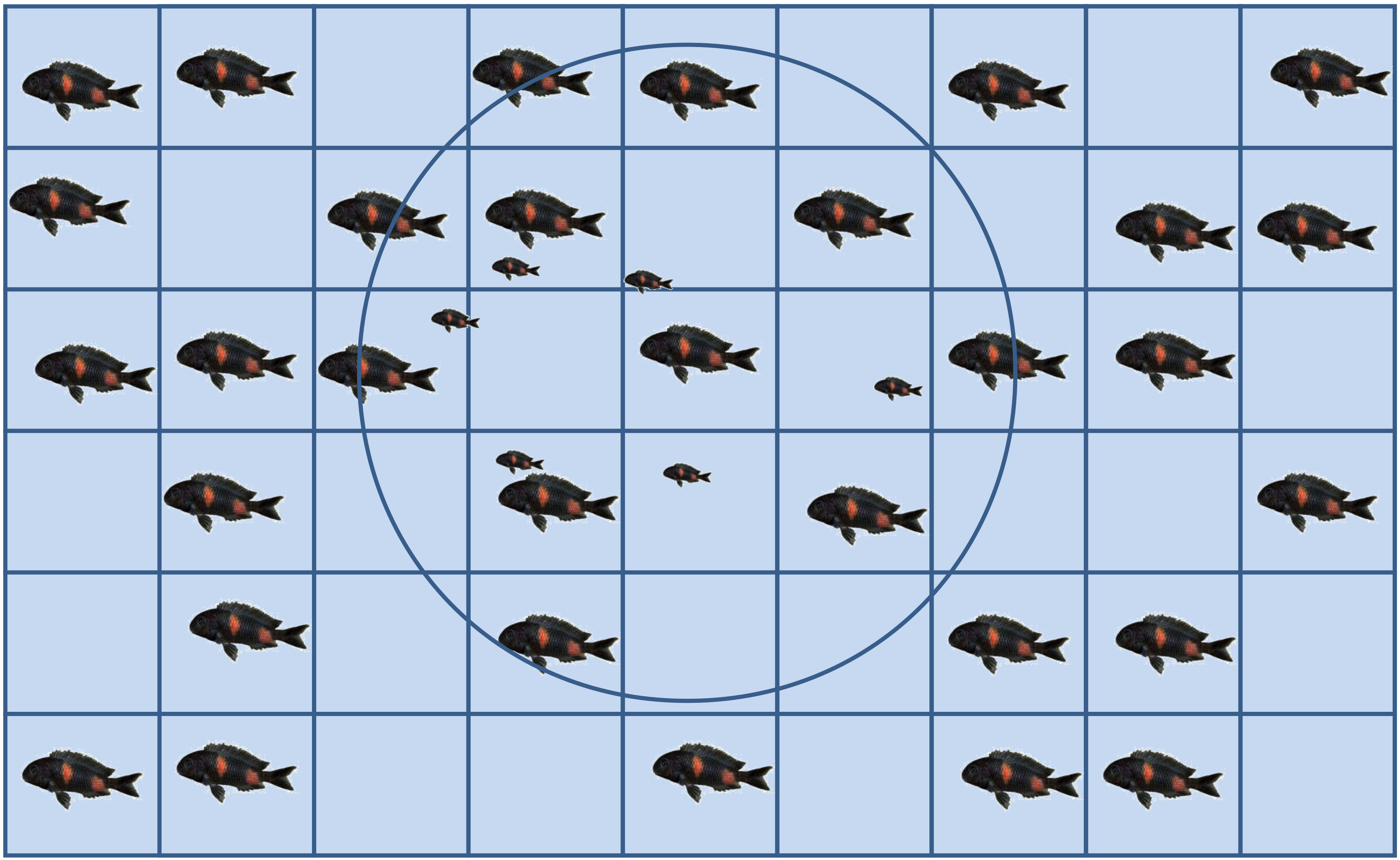
Local Behaviour

Radius of selection for females (depends on the density)



Local Behaviour

Release of juveniles is local

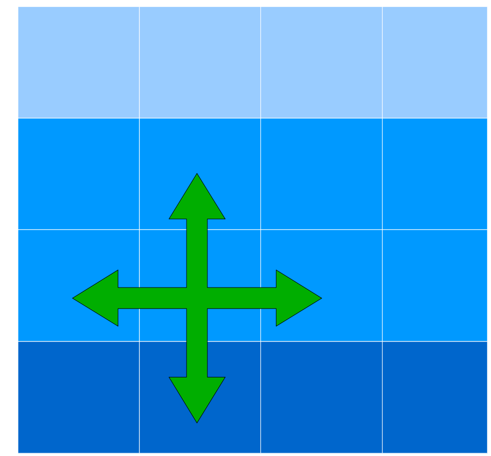


Syntax Extension: Space

$$C \quad ::= \quad < p \in \mathcal{N}^2 \ , \ RULES >$$

$$\text{RULES} \quad \subset \quad \{\langle N \subset \text{Names}, d \in \text{Dir}, r \in \mathcal{R}^+ \rangle\}$$

$$\text{Dir} = \{(0,1),(0,-1),(1,0),(-1,0)\}$$



and so Automata and Transitions have to change accordingly:

$$\begin{aligned} A \quad ::= \quad & \langle n \in \text{Names} \ , \ p \in \mathcal{N}^2 \ , \ \text{STATES} \ , \\ & S \in \text{STATES} \ , \ F \subseteq \text{STATES} \ , \ \text{TABLE} \rangle \end{aligned}$$

$$\begin{aligned} \text{TRANS} \quad ::= \quad & @r \mid \downarrow n@r \mid \uparrow n@r \\ & \mid \text{consume}(n)@r \mid \text{emit}(n)@r \\ & \mid !A(new())@r \\ & \mid \text{up}@r \mid \text{down}@r \mid \text{left}@r \mid \text{right}@r \end{aligned}$$

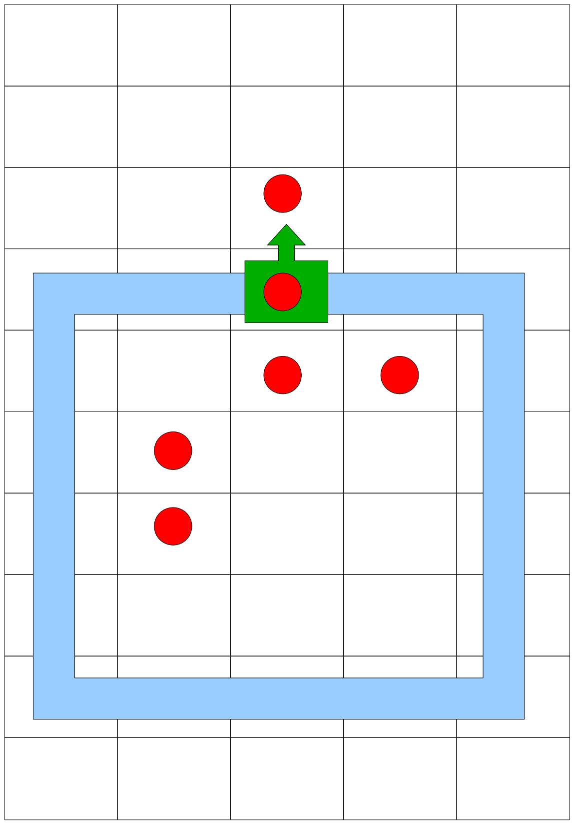
Features

With the proposed syntax it's easy to:

- create barriers/containers
- create gateways/receptors
- specify direction-wise permeability rules

Diffusion time proportional to density comes for free.

Different travel speed for different agents/particles.



Ad-Hoc Solution: F# Simulator

Since we still lack actual simulation abilities, an ad-hoc simulator was created.

Individual-based model of fishes in very long and thin coastal areas.

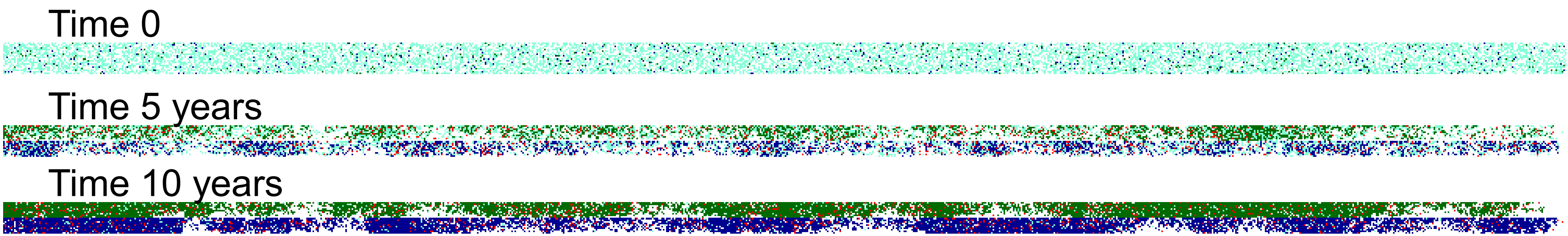
Local behaviour, density-based fitness, logistic model for population growth.

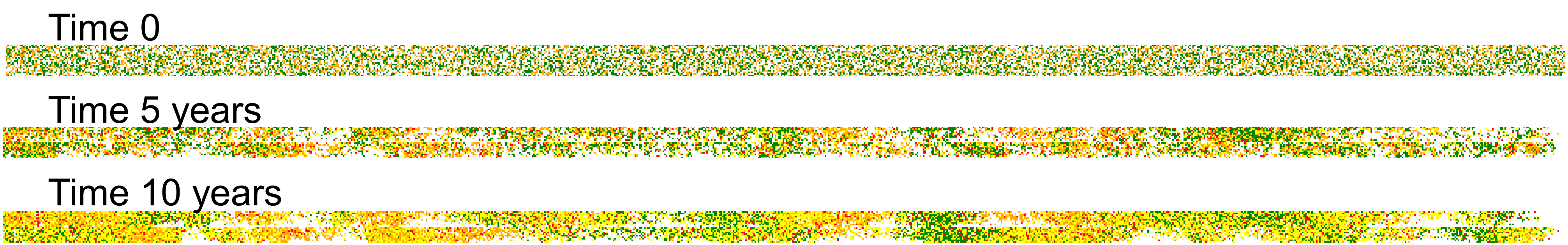
```
member this.updateState(s:simulator):unit =
    if(s.time >= this.nextStateChangeTimer || (this.sex = fishSex.female && this.state = fishState.free)) then
        let nextState, nextEventTime =
            match this.sex with
                | fishSex.male ->
                    match this.state with
                    | fishState.coupling ->
                        this.partner <- None
                        fishState.resting, TOOLS.MALE_RESTING_TIME(s.lowrest)
                    | fishState.resting ->
                        fishState.free, -1
                    | fishState.free ->
                            fishState.free,-1
                    | fishState.dead ->
                        fishState.dead,-1
                    | _ ->
                        failwith "!"
                | fishSex.female ->
                    match this.state with
                    | fishState.coupling ->
                        let nextTime =  this.rnd.Next(TOOLS.MIN_PREGNANT_TIME, TOOLS.MAX_PREGNANT_TIME )
                        let trovato_spazio = this.FindEmptySpaceAndMove(s)
                        if trovato_spazio then
                            //sistemo il maschio, che va a riposo
                            this.partner.Value.partner <- None
                            this.partner.Value.state <- fishState.resting
                            this.partner.Value.nextStateChangeTimer <- s.time + TOOLS.MALE_RESTING_TIME(s.lowrest)

                            fishState.pregnant, nextTime
                        else
                            let caso = this.rnd.NextDouble()
                            if caso >= 0.5 then...
                            else...
                    | fishState.pregnant ->
                        let childNr = this.giveBirth(s)
                        let nextTime = this.rnd.Next(TOOLS.MIN_RESTING_TIME, TOOLS.MAX_RESTING_TIME )
                        this.partner <- None
                        fishState.resting, nextTime
                    | fishState.resting ->
                        fishState.free, -1
                    | fishState.free ->
                        if this.rnd.NextDouble() * 100.0 < TOOLS.percentageOfFreeFemalesCoupling
                            then
                                this.couple(s)
```

Early Results

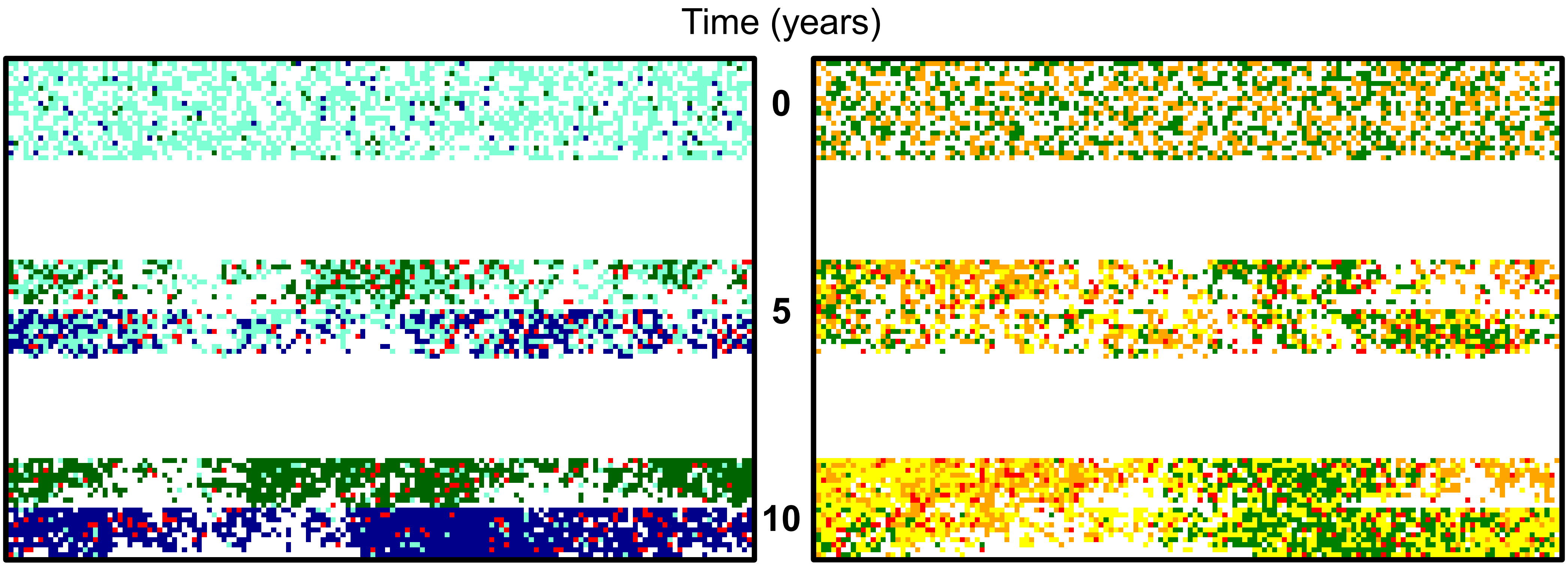
Change of ecology trait and phenotype in time.



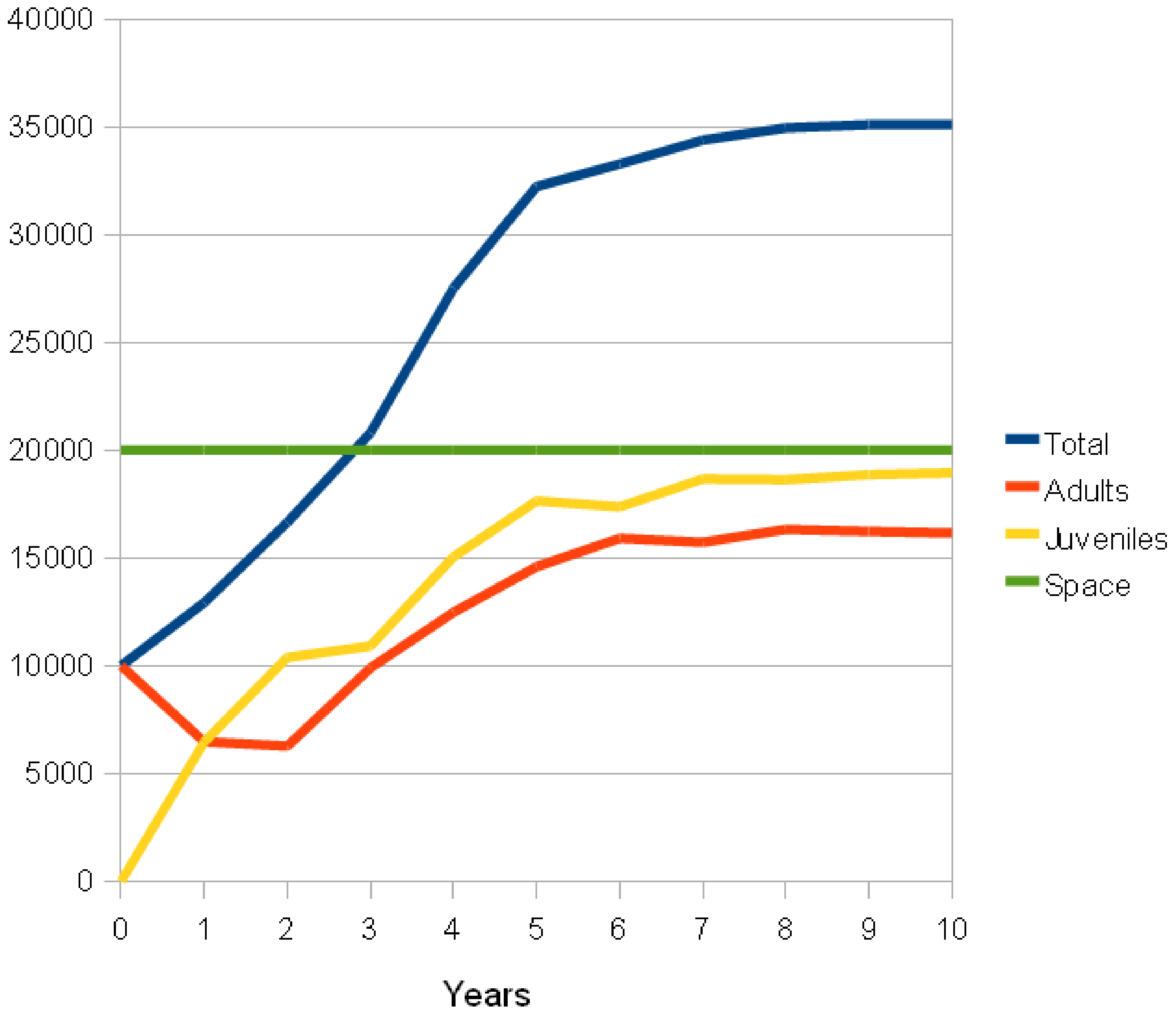


Early Results: Zoom-in

Change of ecology trait and phenotype in time.



Early Results: Population



Nicely simulated:

Population growth to environment limits

Dynamic stabilization

Juveniles over adults ratio

Still missing and future work

Promoters and inhibitors (Turing equivalence?)

Space occupation and radius of interaction

Time intervals (Time scalability)

Creation and destruction of barriers →
Cell properties modified by agent's rules

Modelling and simulating tools

Publications

Zuffi, Rama, Milazzo, Maggiolo Schettini, Barbuti
"Headstarting in the European pond turtle, Emys orbicularis: a computational approach and a proposed model for management plans"
in Seventh Annual TSA Symposium on Conservation and Biology of Tortoises and Freshwater Turtles, 2009

Barbuti, Lepri, Maggiolo-Schettini, Milazzo, Pardini, Rama
"Simulation of Kohn's Molecular Interaction Maps Through Translation into Stochastic CLS+"
in PSI 2009 Proceedings, Lecture Notes in Computer Science LNCS 5947, 2010

Barbuti, Maggiolo-Schettini, Milazzo, Pardini, Rama
"A Process Calculus for Molecular Interaction Maps"
in MeCBIC 2009 Proceedings, Electronic Proceedings in Theoretical Computer Science EPTCS 11

Main references

Ambients
- Cardelli - Artificial Biochemistry
- Cardelli, Gordon - Mobile Ambients

Automata
- Lynch, Attie - Dynamic Input-Output Automata
- Lanotte, Maggiolo - Dynamic Hierarchical Machines
- Barbuti et al. - Timed P Automata

Population
- Grimm - Ten years of individual-based modelling in ecology
- Dunning Jr, et al. - Spatially Explicit Population Models

Speciation
- Gavrilets - Models of speciation
- Gavrilets, Salzburger, et al. - Case studies and mathematical models of ecological speciation

Tropheus
- Salzburger, Sturmbauer et al. - Colour-assortative mating among populations of *T.moorii*
- Salzburger, Sturmbauer et al. - Lake Level Fluctuations Synchronize Genetic Divergences [...]

Thank you