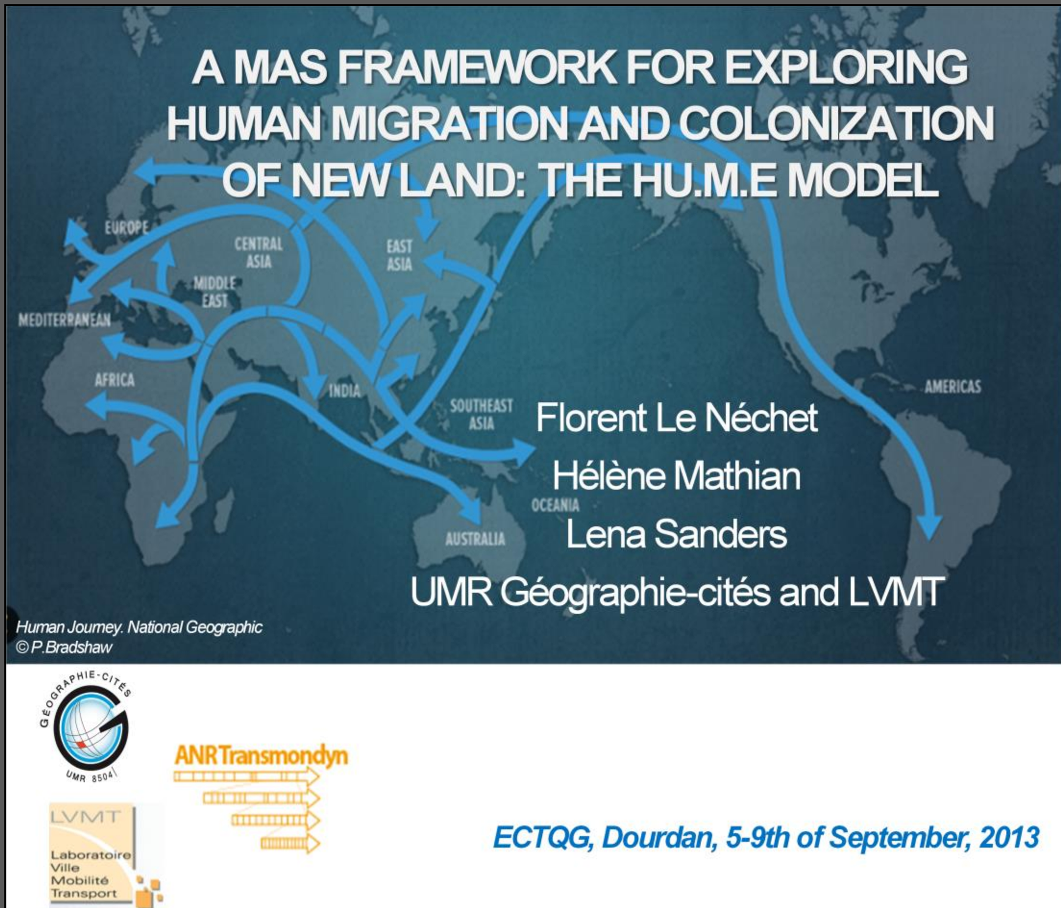
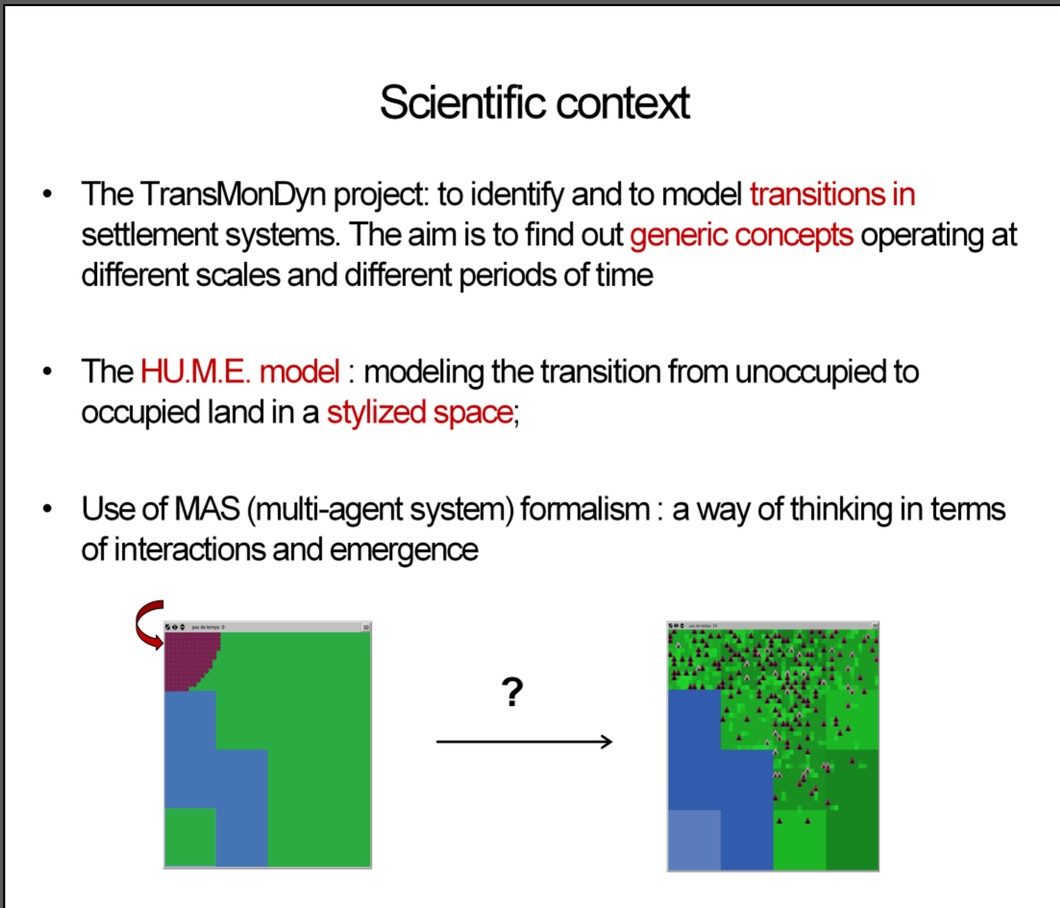


The aim of the present work is to use the framework of multi-agent systems to develop a model for exploring the ways new land is colonized through migration. The empirical facts relate to our ancestors' colonization of the world.

The map describes, in a stylized way, the main migration roads of groups of *homo sapiens* who started their outmigration from Africa about 70 000 years ago.



The scientific context is that of the TransMonDyn project.

Among the transitions studied in this project, “Out of Africa” has a specificity: rather than concerning change in an already established settlement system, the transition is concerned with the colonization of new uninhabited land by migration.

At the global scale, the planet evolves from a concentration of *homo sapiens* in Africa to a spread of our ancestors to the whole planet. The HU.M.E. model has been developed in this framework, in order to explore the conditions for a new continent to be successfully populated.

The model has been developed with a multi-agent formalism.

Aim of the HU.M.E model

- To explore the conditions for success *versus* failure of the colonization of a new land

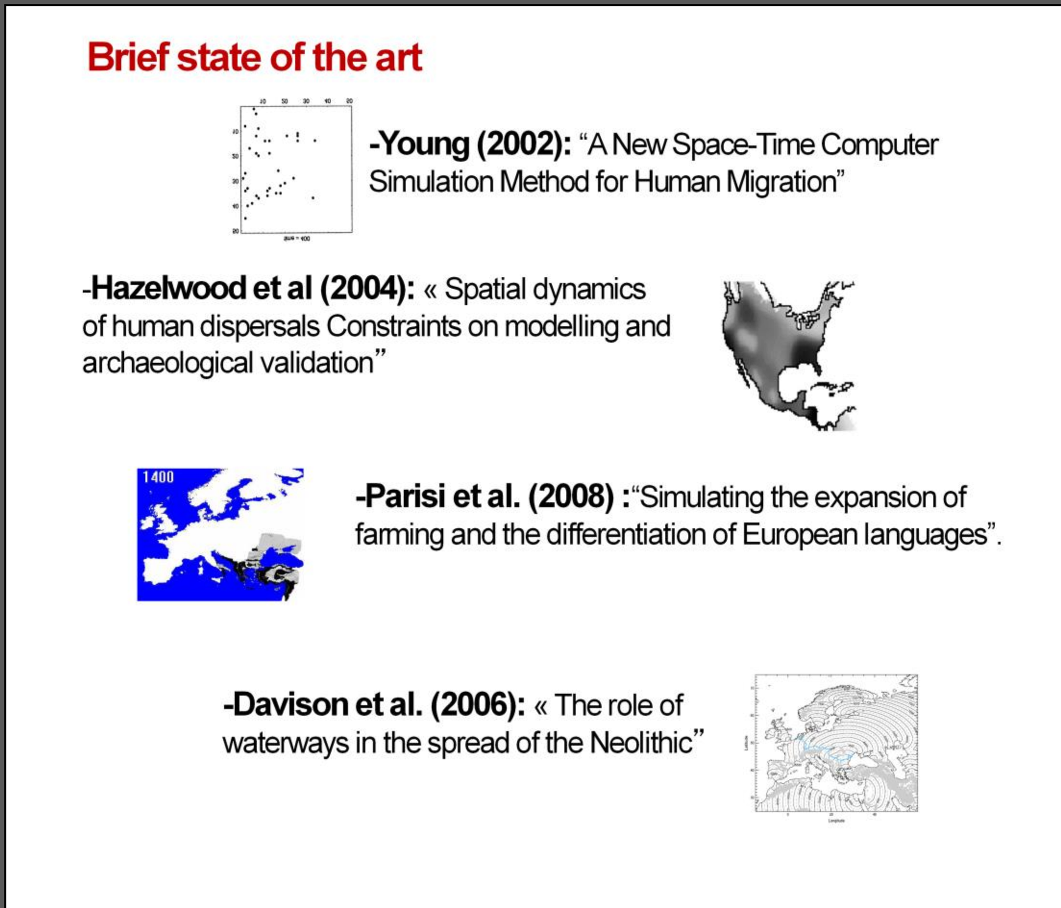
- Effects of the interaction between:
  - environmental constraints,
  - spatial interactions and technological innovation

  on the success of migration

There are not many tracks of these early human migrations. There is a long story of attempts, success, failures of which we only know some pieces. Some attempts has led to a deadlock, such as the Skhul / Qafzeh hominid when others are at the origin of today's world settlement.

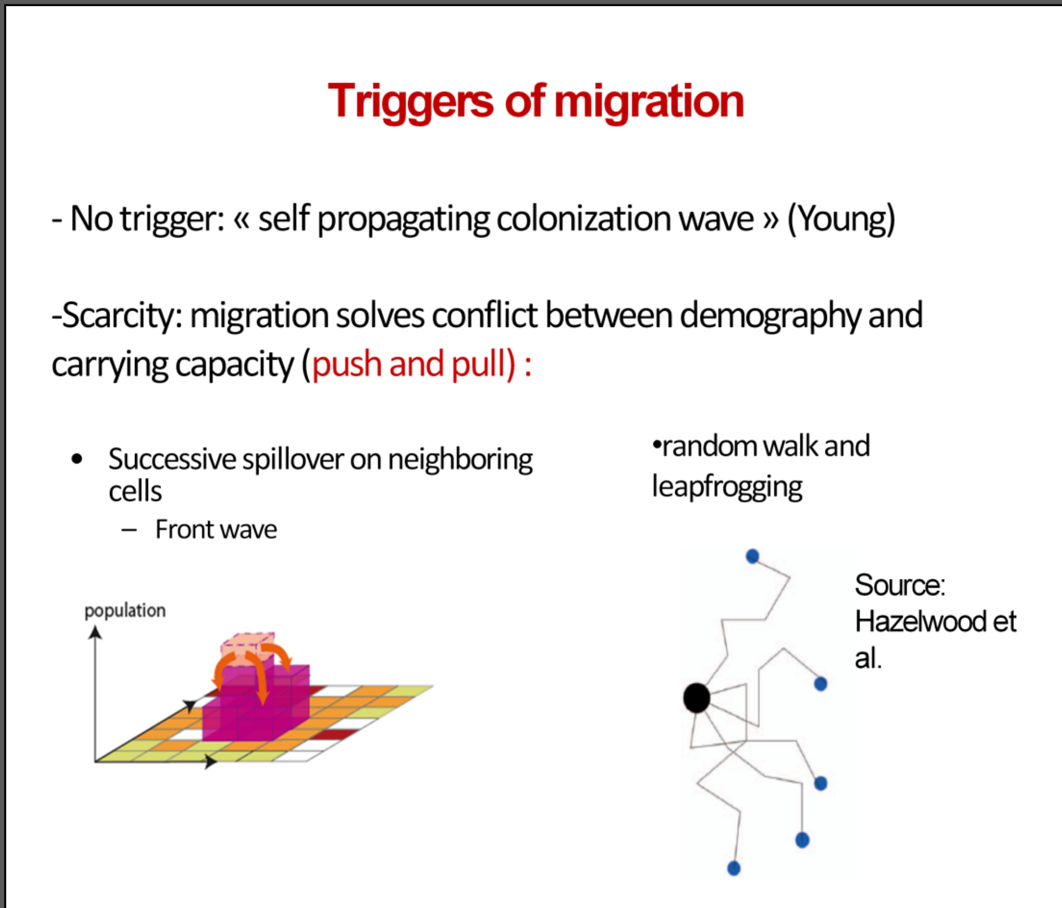
The aim of the HU.M.E. model is to explore the effects of different hypotheses on the success or the failure of the colonization of a new land. Some hypotheses concern appearance and spread of innovation according to the way groups of humans interact. Other hypotheses concern environmental change, with the introduction of different kinds of perturbations.

Rather than trying to reproduce empirical facts, the approach consists in using the MAS (Multi-Agent System) as a tool to realize and explore with simulations a thought experiment.



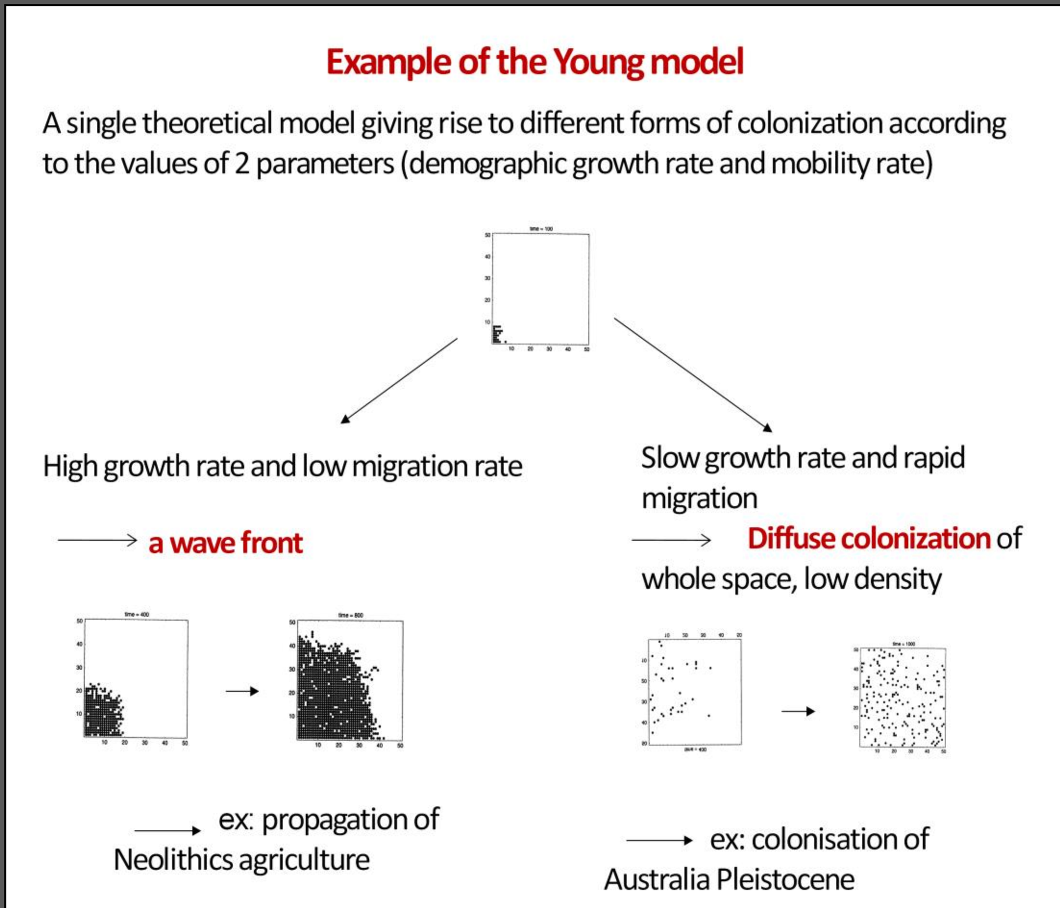
Let us go through a very brief state of the art about long distance migration models. A first distinction can be made according to the level of abstraction of geographical space: Young (2002) considers an abstract homogeneous and isotropic space where agents move (we come back to this case a bit later). The other works quoted here refer to a space which is rooted in a realistic geography.

Parisi et al. developed a model incorporating demographic growth and diffusion. The decision to migrate depends on the state of neighboring cells according to their agricultural potential (carrying capacity). In the initial situation (9,000 BP) only one cell is occupied by a population of farmers. As the number of farmers increase, part of them migrate to a neighboring cell. That way the authors simulate the expansion of agriculture in Europe during the Neolithic. Dealing with the same question, Davison et al. (2006) use a two dimensional reaction-diffusion model and introduce differences in the speed of mobility according to the proximity of rivers and coastlines. Hazelwood and Steele (2004) use a similar model to explore the spread of Neolithic in Europe and the first peopling of America with gatherer-hunters groups. The same model is used for these two processes, the parameters only varying between the two cases.



Different chains of causality may lead to migration : - scarcity of resources, which triggers a group or a part of a group to leave a place to search for better resources; - a conflict internal to a group or between groups, desire of change, religious belief, or any specific reason which the modeler choose not to specify. Such move, a bit improperly named on this slide as “no trigger”, is then modeled with a random term (case of Young, 2002).

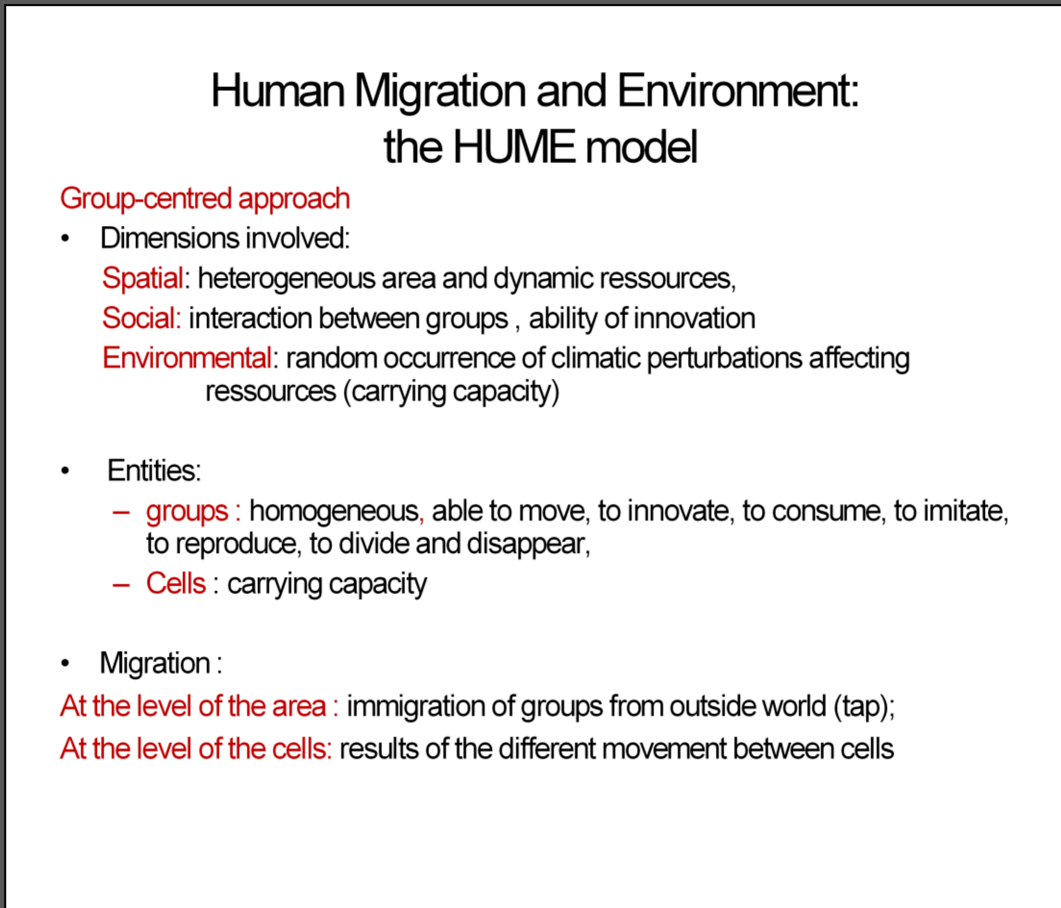
In the case when migration is the consequence of an insufficient carrying capacity, the move can take the form of successive spillover on neighboring cells (case of Parisi and al. 2008) or that of a random walk with leapfrogging or not (Hazelwood and al., 2004).



In the Young model (2002), space is represented by a two dimensional abstract grid. It is empty at the initial state and a flow of agents (representing either individuals or groups) penetrate in the area from the South-West. The author uses a Monte Carlo method to formalize the two processes involved: 1- demographic change: each agent has a certain probability to die and to give birth at each iteration; 2- migration: agents move through a random walk. The results are following:

- If demographic growth rate is high and migration rate low, there is a front wave that moves slowly, in a progressive manner. Diffusion of farmers in Europe during the Neolithic illustrates this case and also the North-American colonization by the Europeans;

- If demographic growth rate is low and migration rate high, there is no front: the whole space is invested, but in a diffuse manner and with an overall low density. The colonization of Australia during the Pleistocene is one example of such case.



The approach adopted to consider space in the HU.M.E. model is intermediary relatively to the models in the literature: there is neither an homogeneous and isotropic space, neither is it associated to a specific geographical area. Nonetheless, space is heterogeneous and the resources are dynamic.

Let's present a first insight in the model through the three dimensions involved in it :

The Spatial one: the story takes place in an heterogeneous area. The area is modeled by a set of cells which differ in their carrying capacity.

The social one: the story is about groups that have the ability to innovate and to interact. There are competition and imitation mechanism involved. Space plays a role of interface for these interactions.

The Environmental one: there are occurrences of climatic perturbations affecting the effective resources that are randomly distributed over time.

So formally the entities are :

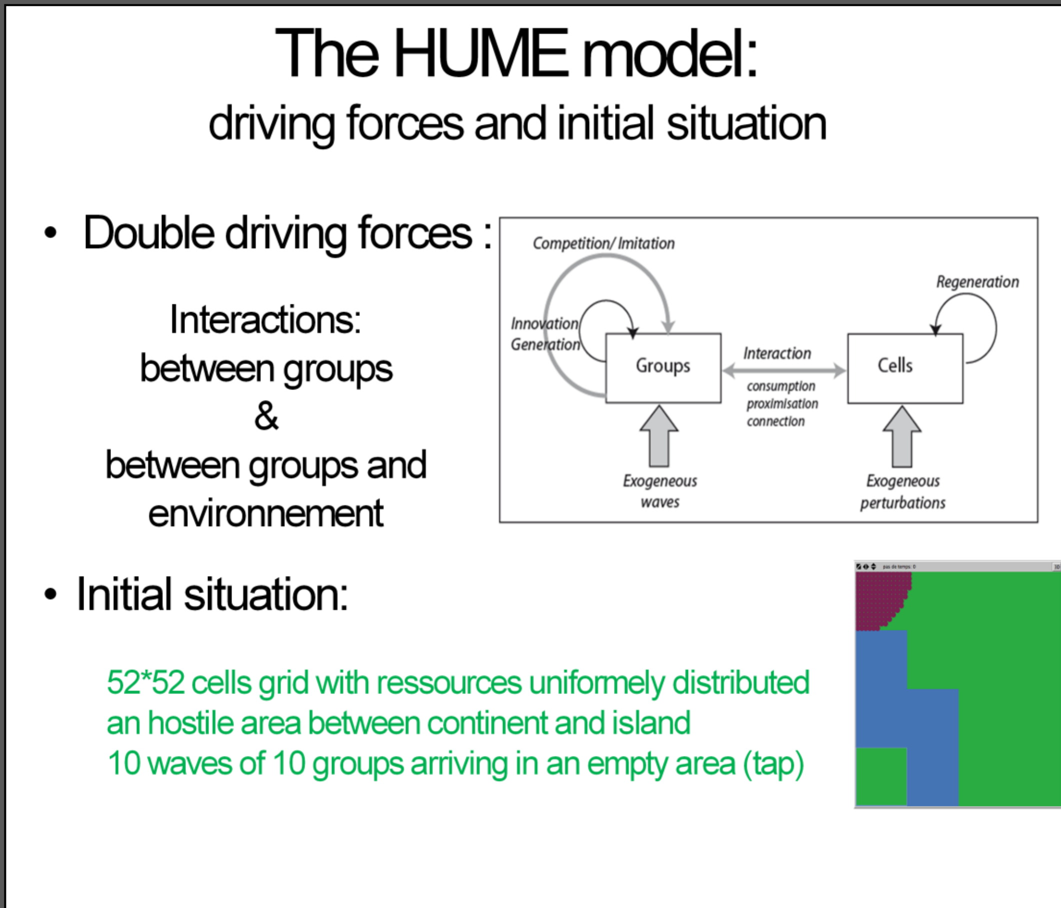
- **groups** which are homogenous and whose activity are controlled by probabilities; the groups move, innovate, consume, imitate, reproduce, divide and disappear.

- **cells** are the component units of space. They carry resources and are initially homogeneous, but under the impact of perturbations and groups' pressure the distribution of the resources got heterogeneous.

The driving process is migration which is of 2 kinds operating at 2 levels :

1- At the level of the whole area with migration flows coming from the outside: immigrating groups from outside world penetrate the area via a "tap";

2 At the level of the cells: a group migrates to another cell when its carrying capacity is insufficient.



At this stage, it is possible to schematise the **functioning (dynamic) of the model** by the interactions between the two types of entities: groups and cells.

Let's see the different elements involved:

- First **the exogeneous components**: migration from outside, cycles of perturbation on the environment.

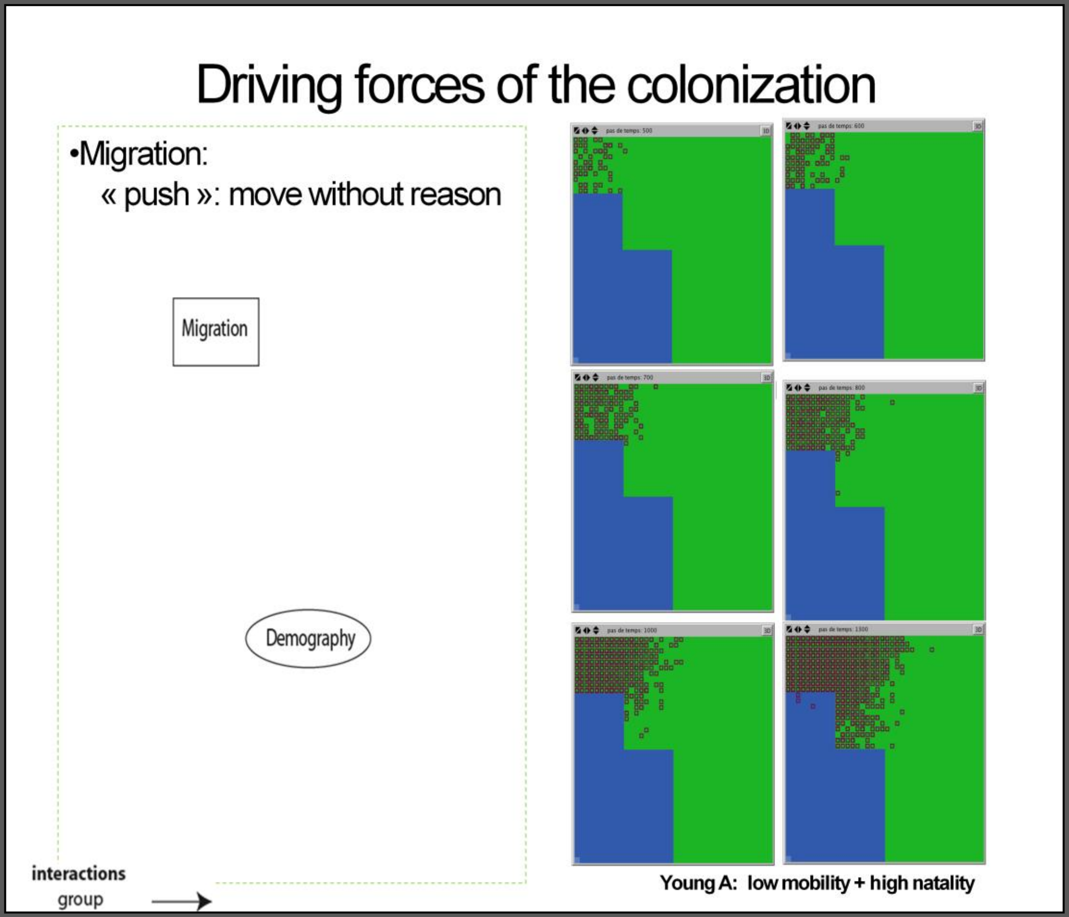
- Second **the intern entity dynamic**: groups reproduce, innovate, and accumulate the energy they need to move (move has a cost) - cells' resources regenerate

- Third **the interactions between groups:** imitation for technology, competition for exploiting local environment

- At last the **interactions between groups and cells :** they concern the consumption of resources and they allow interactions between groups.

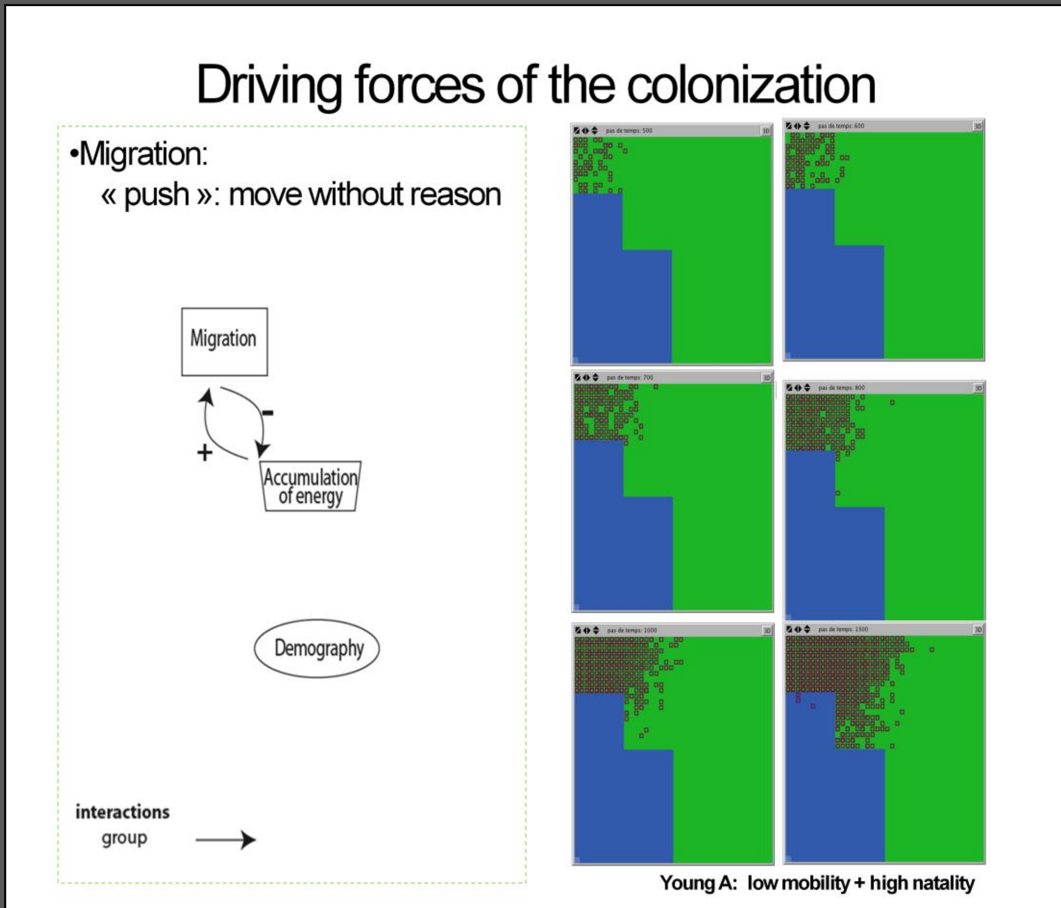
So, at first we have a grid of 52*52 cells where resources are uniformly distributed (that is in green). There is an hostile area (in blue) between the continent and an island. In a first phase we will focus on what is happening on the continent.

The simulation starts with 10 waves of groups arriving in the empty area (colonization as a tap)



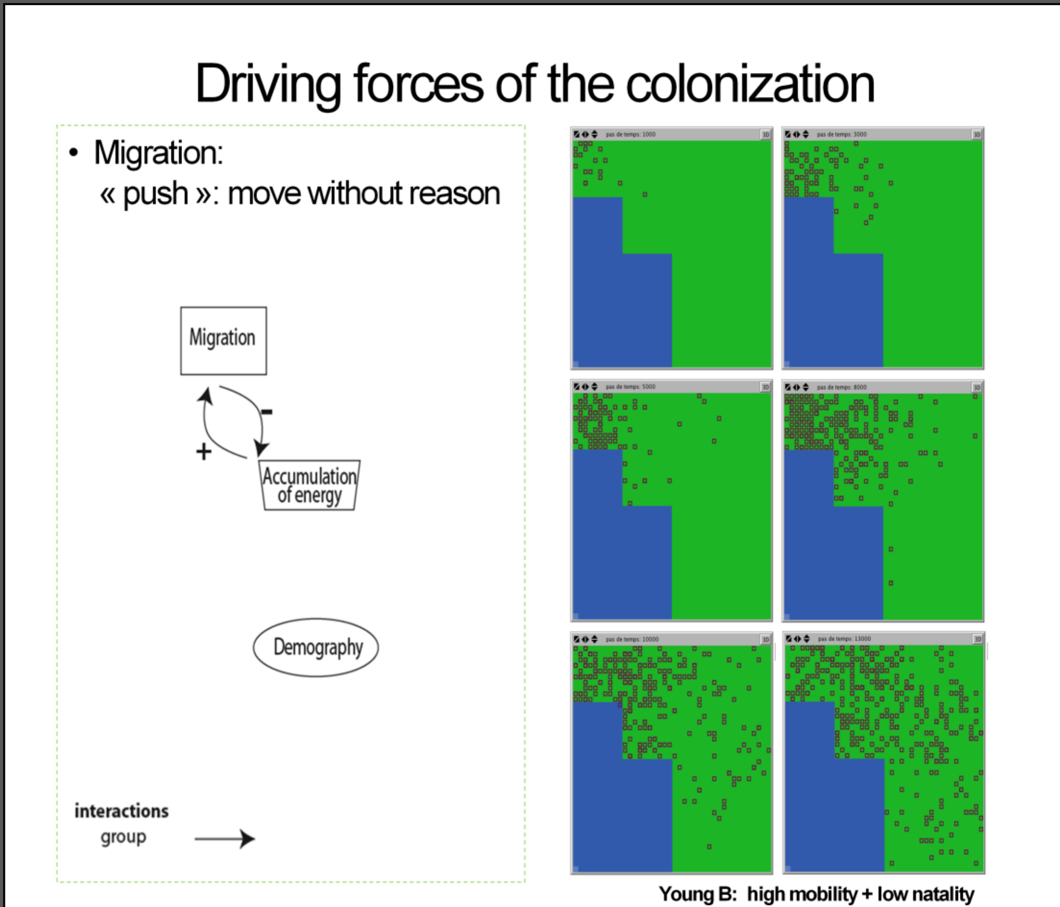
To describe the dynamic of the model we decomposed it into **generic mechanisms** that interact. We will present them in a hierarchical building.

The first stage is based on the combination of **migration and demography**: groups have a probability to move without reason, groups move from one cell to another without any knowledge (random walk) and they have a probability to split (which stands for the growth process).

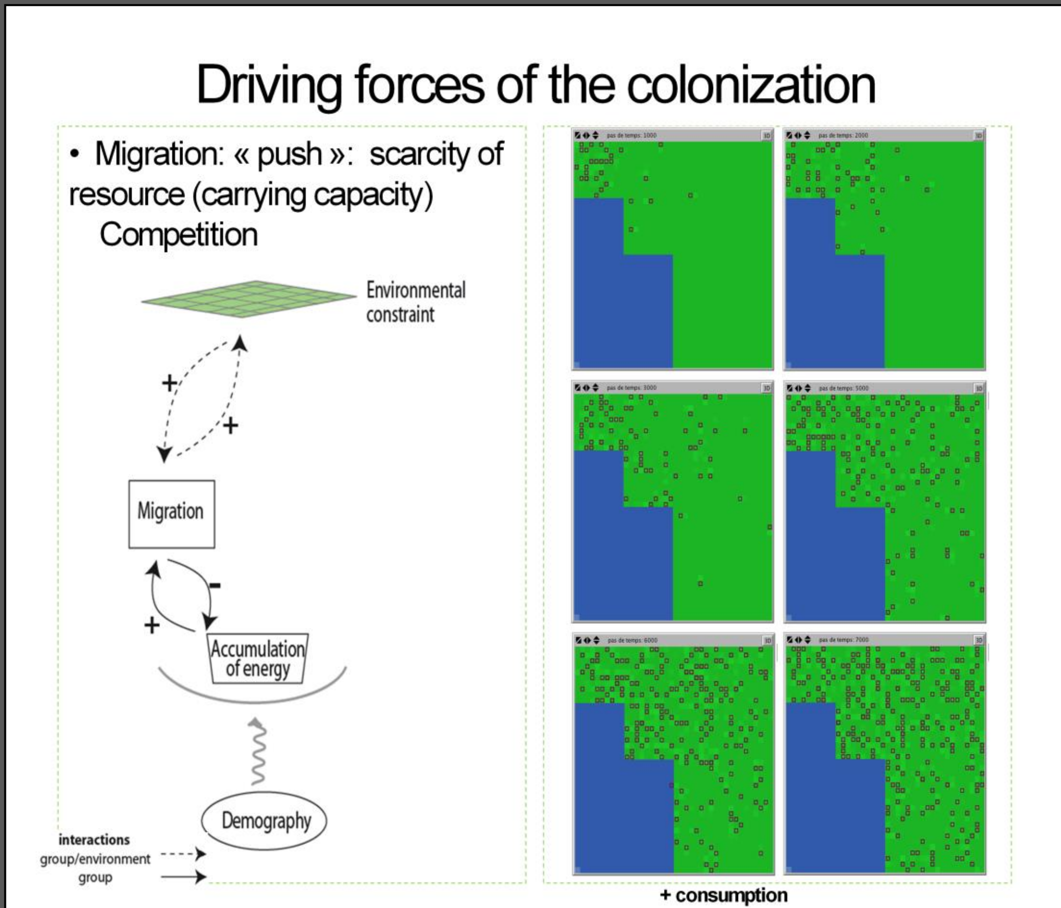


Then we have to add the notion of **energy:** moving has a cost, and we have introduced a sort of accumulation mechanism. When groups don't move they accumulate energy and when they move they burn energy. This is the first constraint of the model: without energy a group disappears.

As a reference, with only these three mechanisms, the model is quite close to the Young's one. We illustrate it with a specific combination of parameters: for instance **a low probability of mobility and a high rate of natality** leads to a population wave front

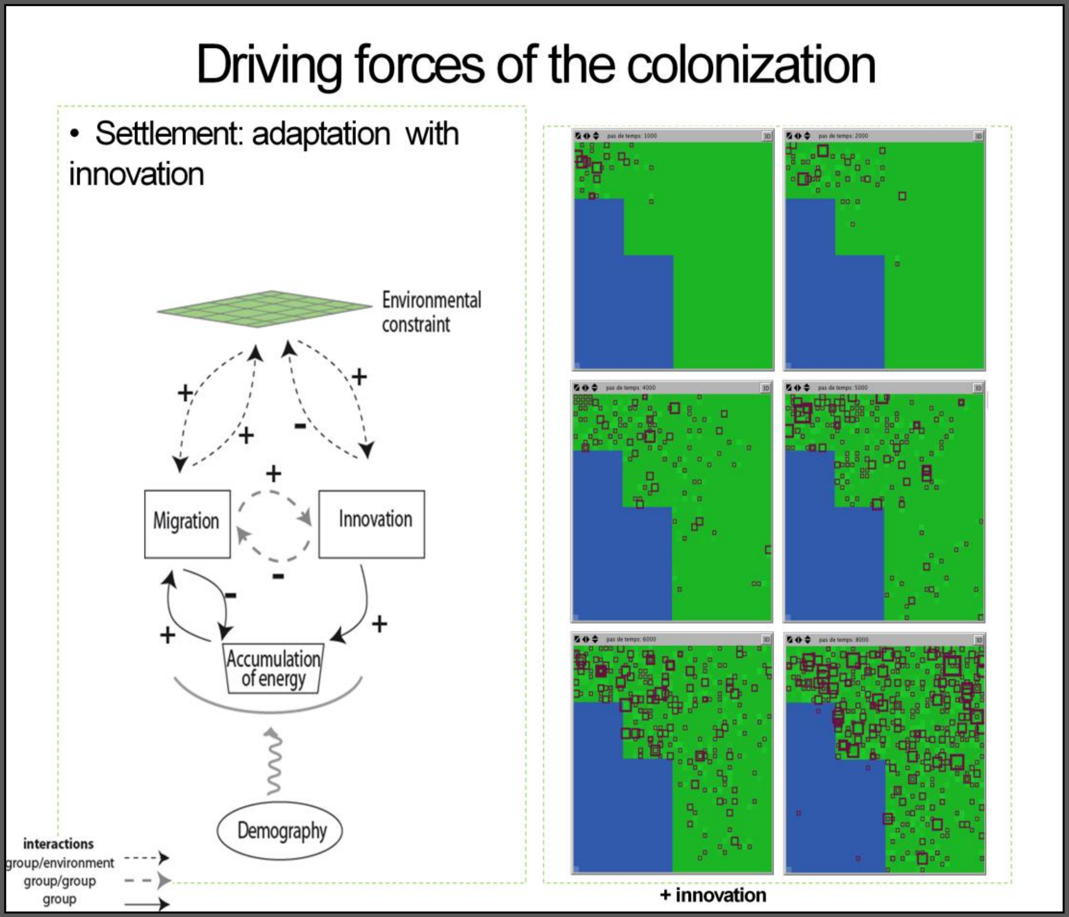


And **with high mobility and low natality** , which correspond to the other alternative of Young's model, the evolutions goes to a more extensive spread of the population.

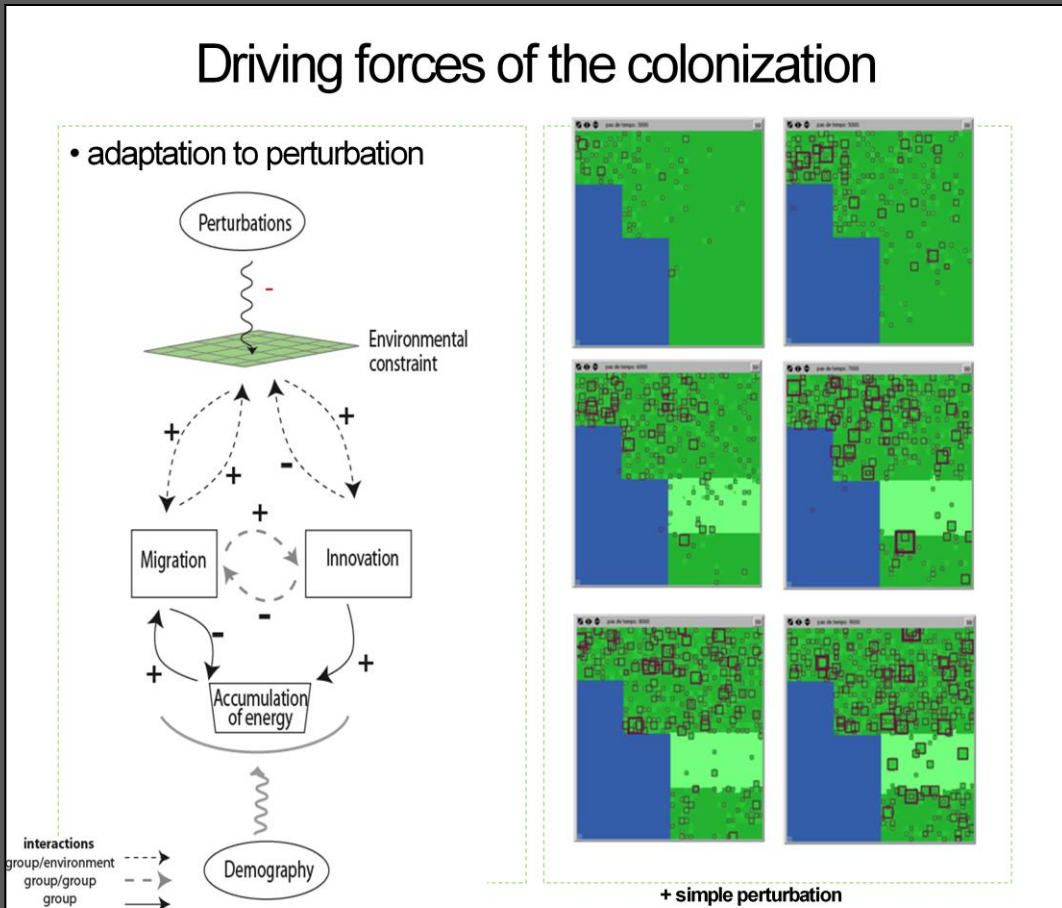


A motivation to move is linked to the **carrying capacity** of the cell. This is the second constraint. Consumption of resources has now been introduced: when there are not enough resources, groups have to move. And when they move, they may move to an already inhabited cell : the crowding may lead to an overpressure on the environment. At the opposite, when a cell is left empty, a process of regeneration begins at the height of the carrying capacity.

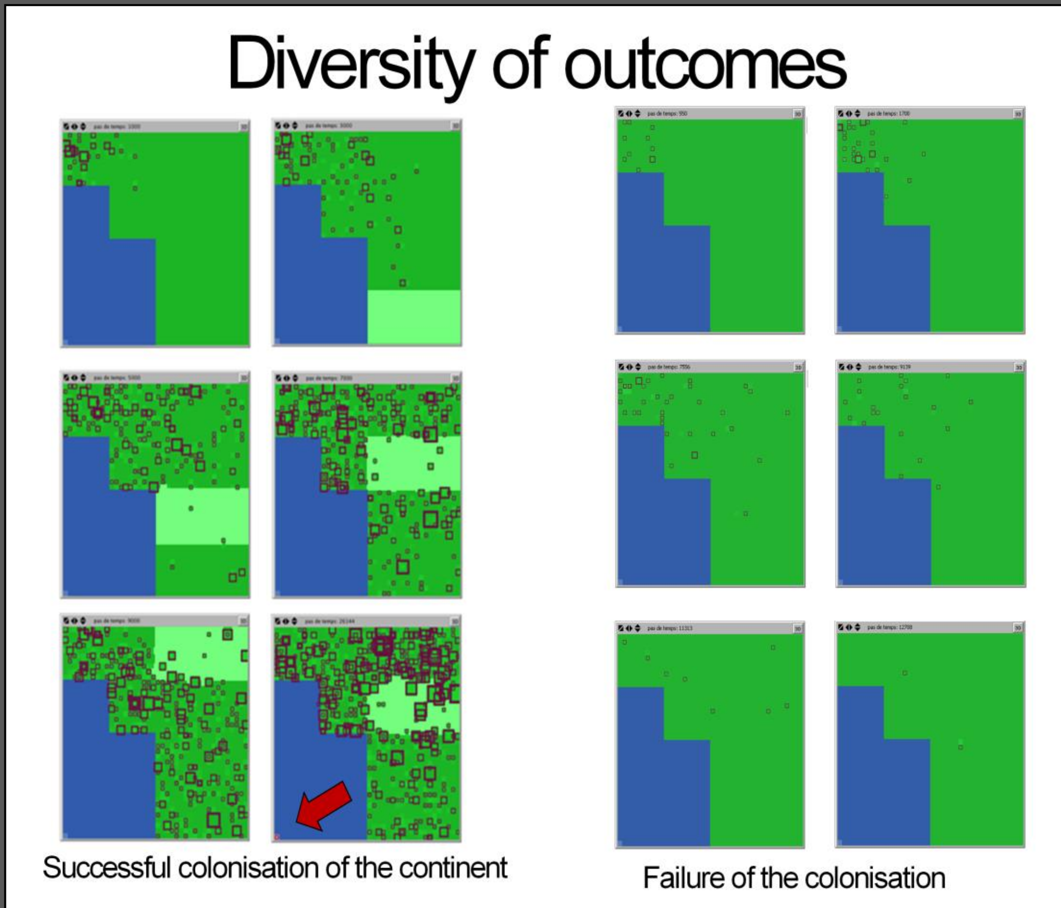
The cartography uses the color of the cells for representing the level of the remaining resources.



An alternative to the migration is **innovation**: innovation, increasing the exploitation performance, allows to stay with the same amount of resources. Innovation will influence the settlement process. In a same cell there is diffusion of the highest technological level to all the groups, according to a mechanism of imitation. Size of symbols associated to the groups are proportional to their level of technology.



And finally there are the **pertubations**: the illustration shows a simple perturbation that arrives once and stays. But we computed more tricky perturbations that arrive as waves in order to observe how the collective pattern is pertubated and how it may adapt.



All these processes can potentially lead to a diversity of outcomes. A simulation with low demography, high mortality for instance will lead to the failure of the colonization, whereas other parameters will tend to a successful colonization of the continent. The stochasticity of the model is high, and therefore for some values of the parameters, we can observe a diversity of outcomes, as is shown in the figures. We decide to adopt a quantitative method to increase the comprehension of the model : this requires to compute indicators that would caracterize the state of the colonization at each timestep.

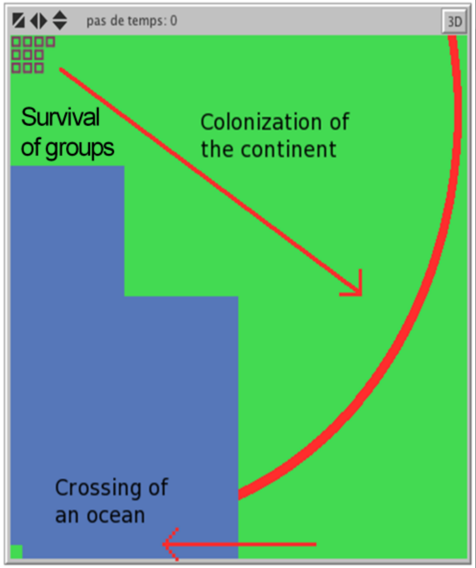
How to measure success of colonization ?

- Survival of groups
- Colonization of a whole continent
- Crossing of an ocean

In order to characterize the simulation results, a set of indicators were computed. Their aim is to measure the success or failure of the colonization.

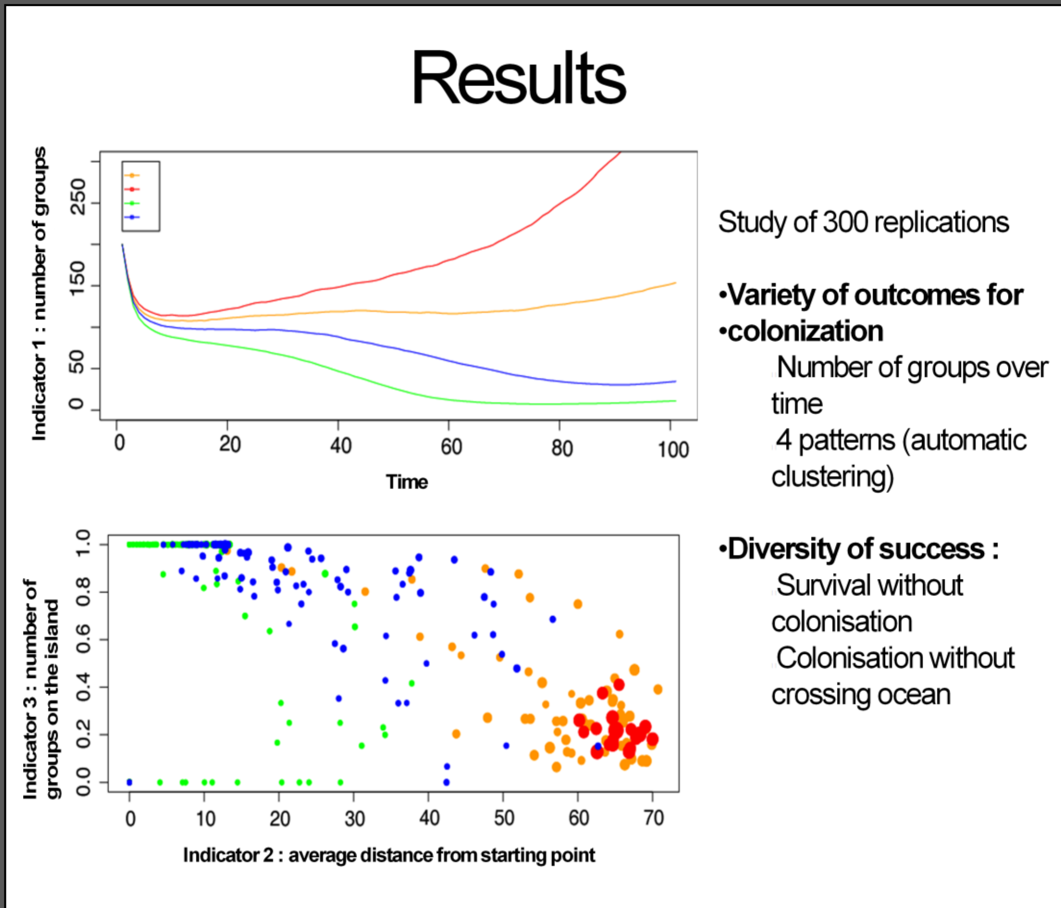
Outputs : three indicators of success

1. Number of groups at time t = 20000
2. Average distance of groups from the starting point
3. Number of groups on the island at time t = 20000



The way we decided to implement these indicators is as follows : because of the open nature of the model (impacted by perturbations over time), it was decided not to try to characterize the system when it reaches an equilibrium ; at the same time, the initialization phase (from the initial conditions to the time when the first group reaches the opposite side of the continent) can potentially lasts long (it depends on the values of the parameters). Hence it was decided to compute indicators of the configuration of the system at a time when, according to the range of variation of the parameters, most of the simulations will have had finished their initialization phase. Theses indicators are:

- The demography of the groups, that characterize their survival ;
- The position of the groups in space: because the colonization starts from the upperleft corner, we measured the position of the colonization « wave » from the starting point;
- In cases where the technical improvement made it possible for groups to cross the sea from the continent to the island, we reported the number of groups that achieved the crossing.

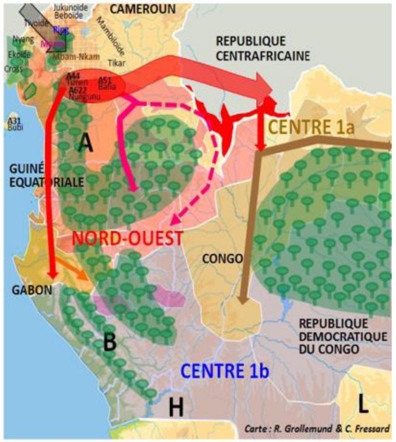


This quantitative framework allowed us to explore the relative importance of the different processes involved, by assessing the relative influence of each parameter of the model on the output indicators. As was explained in slide 16, the stochasticity of the model is high and some set of parameters lead to a diversity of outcomes. This is what reveals the upper figure where, among 300 replications of the same simulation, 4 categories of replications have been detected, with at the extremities successes (red curve : high demography) and failures (green curve : low demography). The lower figure shows the correlation between indicators 2 and 3 of slide 17 : it suggests the existence of two main regimes at the end of the simulation. The red and orange dots show high value of the average distance from starting point and low value of the proportion of groups which have crossed : it means that the colonization successfully filled the entire space and that, in proportion, relatively few number of groups have had a reason or the ability to cross the sea towards the island. At the other extreme, replications that experienced failures have both a small demography (the size of the circles) and a small value of the average distance from starting point, indicating low mobility of groups.

Perspectives

- Sensitivity analysis :
    - Explore the conditions for success / failure / uncertainty
    - Key parameters : innovation, natality, energy accumulation through local consumption

-Confrontation with knowledge of paleolinguists (Coupé & Hombert)
    - TransMonDyn research program
    - If necessary, introduction of supplementary mechanisms
        - Memory
        - Ability to anticipate



Source: Coupé & Hombert

The next step of the HUME model is to be submitted to the critical analysis of empirical specialists, and to implement new processes that are better able to reproduce more complex migration patterns.