Simulação multiagentes: O protocolo ODD

Baseado em GRIMM, Volker; BERGER, Uta; BASTIANSEN, Finn; et al. A standard protocol for describing individual-based and agent-based models. Ecological Modelling, v. 198, n. 1, p. 115–126, 2006.

Jorge H C Fernandes

Computação Experimental

CIC – UNB – agosto de 2021

Usos Potenciais de Modelos de Simulação IBM *Individual-Based Models*

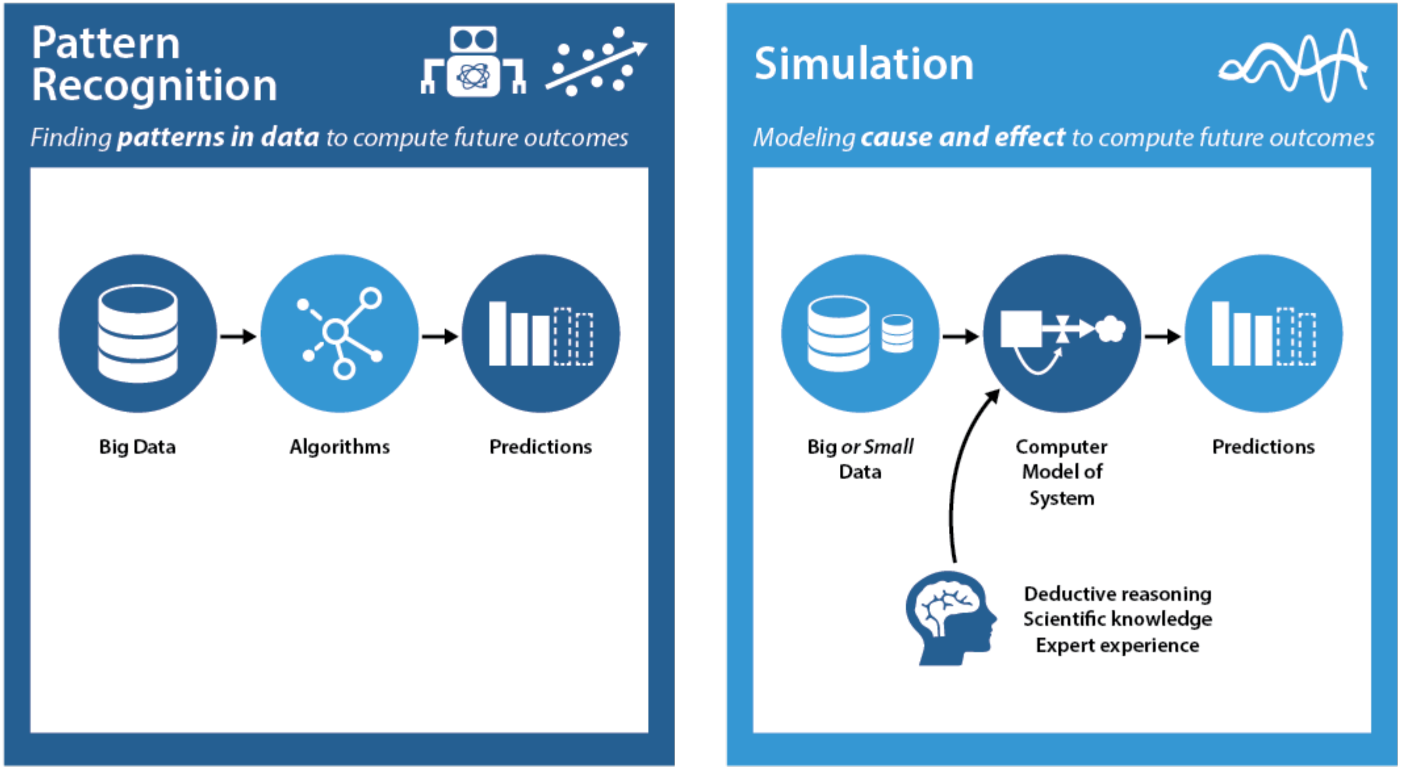
- Simulation models that describe individual organisms or, more generally, “agents”, have become a widely used tool, not only in ecology but also in many other disciplines dealing with **complex systems** made up of autonomous entities, including the social sciences, economics, demography, geography, and political sciences.
- Individual-based models (IBMs) allow researchers to study how
  - **system level properties** emerge from the (sistema – estrutura social)
  - **adaptive behaviour of individuals** (indivíduo -)
  - as well as how, on the other hand, the system affects individuals.
- IBMs are important both for theory and management because they allow researchers to consider aspects usually ignored in **analytical models**: variability among individuals, local interactions, complete life cycles, and in particular individual behaviour adapting to the individual’s changing internal and external environment.

Problemas com a Complexidade e Compreensão de Simulação IBM

- “.. the great potential of IBMs comes at a cost. IBMs are necessarily more complex in structure than analytical models. They have to be implemented and run on computers. IBMs are more difficult to analyze, understand and communicate than traditional analytical models.”
- “Particularly critical is the problem of communication. **Analytical models are easy to communicate because they are formulated in the general language of mathematics**. Their description usually is complete, unambiguous and accessible to the reader.”
- “In contrast, **published descriptions of IBMs are often hard to read, incomplete, ambiguous, and therefore less accessible**. Consequently, the results obtained from an IBM are not easily reproduced.”
- “Science, however, is based on reproducible observations. Solving the problem of how to communicate IBMs can only increase their scientific credibility.”

Abordagem analítica versus simulação: Intuição.

Fonte: https://www.dimins.com/blog/2018/01/26/simulation-in-predictive-analytics/

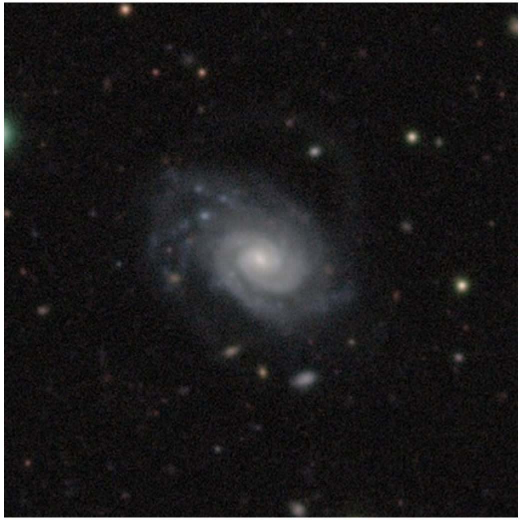


Abordagem analítica versus simulação: Exemplo

Clump Survival and Migration in VDI Galaxies:
an Analytic Model versus Simulations and Observations

Avishai Dekel[1,2⋆], Nir Mandelker[1,3†], Frederic Bournaud[4‡],
Daniel Ceverino[5], Yicheng Guo[6], Joel Primack[7]

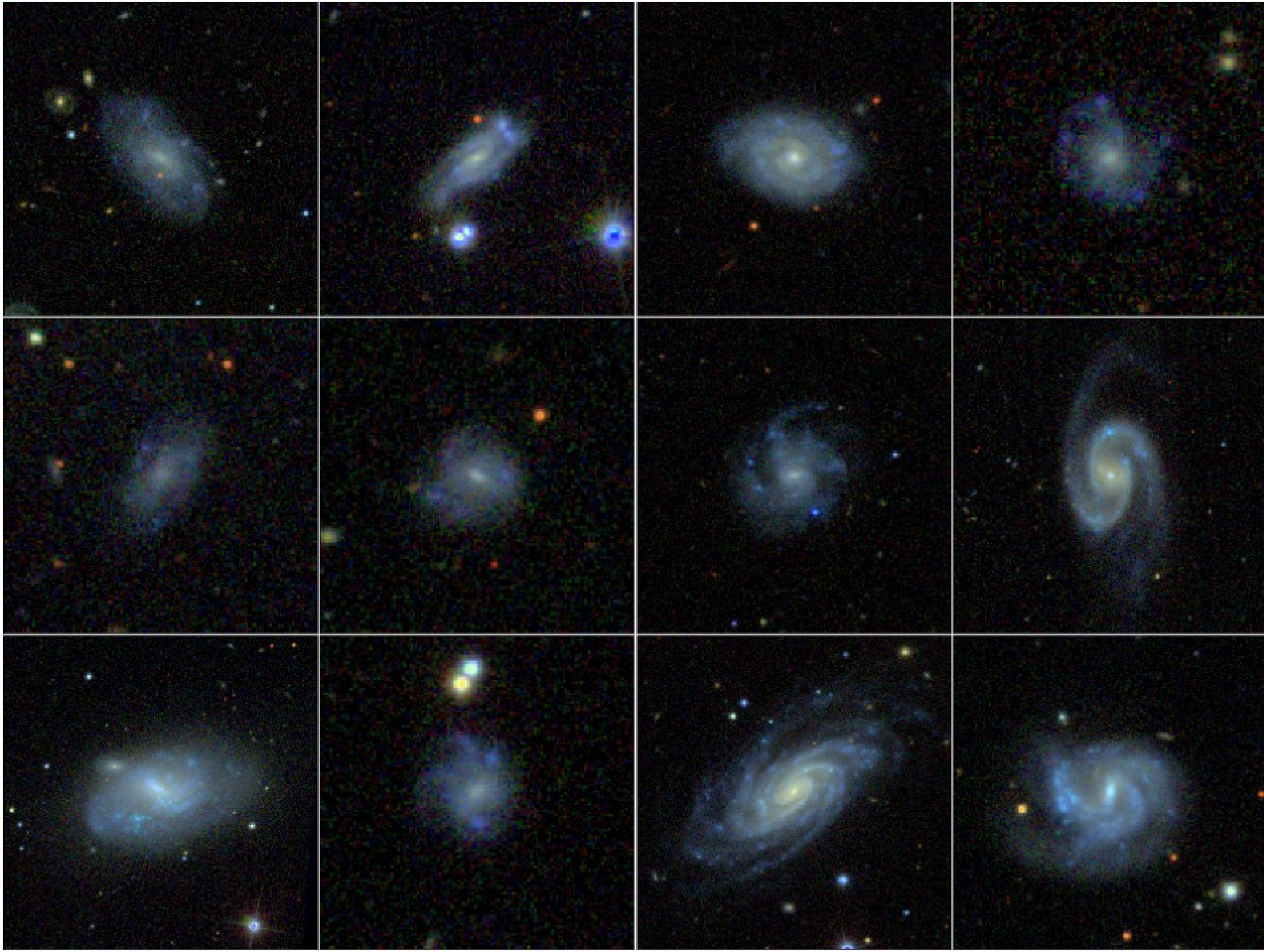
Fonte: https://arxiv.org/pdf/2107.13561.pdf



https://www.legacysurvey.org/viewer/cutout.jpg?ra=60.6468&dec=-11.1467&layer=ls-dr9&pixscale=0.25

Galaxy clumps = small regions within galaxies where stars are being born at a faster-than-usual rate
VDI = Violent Disk Instabilities

Galaxy Clumps. https://blog.galaxyzoo.org/2019/09/18/introducing-galaxy-zoo-clump-scout-a-new-citizen-science-project/



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2 ANALYTIC MODEL: MASS GAIN & LOSS

2.1 Clump migration

$$t_{\rm mig} \simeq 2.1 Q^2 \delta^{-2} t_{\rm d} \sim (10-20)\, t_{\rm d}\,, \qquad (1)$$

$$V_{\rm mig} \sim \frac{1}{10}\,\frac{R_{\rm d}}{t_{\rm d}}\,\frac{M_{\rm c}}{M_{\rm T}}\,. \qquad (3)$$

2.2 Gas accretion onto clumps

$$M_{\rm ac} \simeq \alpha\, \rho_{\rm d}\, (\pi R_{\rm T}^2)\, \sigma_{\rm d}\,.$$

2.3 Star Formation Rate

$$\mathrm{SFR} = \dot{M}_{\rm sf} = \epsilon_{\rm ff}\frac{M_{\rm g}}{t_{\rm ff}} = \epsilon_{\rm d}\frac{M_{\rm g}}{t_{\rm d}}\,, \qquad (11)$$

2.4 Gas Outflow

$$\dot{M}_{\rm out} = \eta \dot{M}_{\rm sf}\,, \qquad (16)$$

2.5 Stellar mass exchange

$$\eta_{\rm s} = \frac{\dot{M}_{\rm s,loss}}{\dot{M}_{\rm sf}}\,. \qquad (18)$$

3.3 Analytic solution for clump evolution

$$\ddot{M}_{\rm g} = 0.5\,\alpha\, t_{\rm d}^{-1} \dot{M}_{\rm s} + [0.5\,\alpha - (\mu+\eta)\,\epsilon_{\rm d}]\, t_{\rm d}^{-1} \dot{M}_{\rm g}\,. \qquad (24)$$

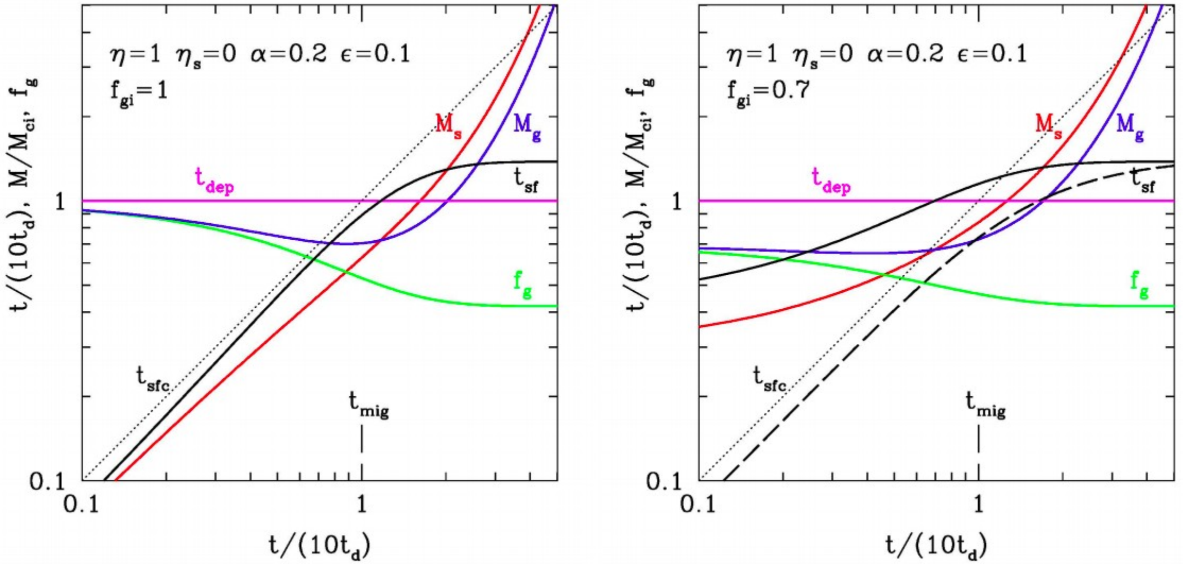

Figure 1. Toy-model evolution of clump properties, for the choice of parameters indicated, and with initial gas fraction $f_{\rm gi}=1$ (left) and 0.7 (right). Shown are clump gas mass $M_{\rm g}$ (blue), stellar mass $M_{\rm s}$ (red), gas fraction $f_{\rm g}$ (green), depletion time $t_{\rm dep}$ (magenta), star-formation time $t_{\rm sf}=\mathrm{sSFR}^{-1}$ (black) and its corrected version $t_{\rm sfc}$ for $f_{\rm gi}<1$, eq. (45) (dashed black), which differs from $t_{\rm sf}$ only when $f_{\rm gi}<1$. We see the phase during migration where the SFR, proportional to $M_{\rm g}$, is roughly constant, such that $t_{\rm sfc}$ is a proxy for the clump lifetime (dotted black). At late times the clump converges to a quasi-steady state with an exponential mass growth and a constant $t_{\rm sf}$, but this is supposed to 'occur' only after the migration is complete. For $f_{\rm gi}<1$ there is an early phase dominated by the initial gas fraction, where $t_{\rm sf}$ is an overestimate of the clump time, but this is properly corrected for by $t_{\rm sfc}$, which is a close lower bound for the clump time.

Abordagem analítica versus simulação

**Clump Survival and Migration in VDI Galaxies:
an Analytic Model versus Simulations and Observations**

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Fonte:
arxiv.org/pdf/
2107.13561.pdf

4 SIMULATIONS

4.1 Isolated galaxy simulations

4.2 Cosmological simulations

We use here two zoom-in cosmological simulations from the `VELA` suite, out of 34 galaxies with halo masses $10^{11} - 10^{12} M_{\odot}$ at $z \sim 2$, which have been used to explore many aspects of galaxy formation at high redshift (e.g., Ceverino et al. 2014; Moody et al. 2014; Zolotov et al. 2015; Ceverino, Primack & Dekel 2015; Inoue et al. 2016; Tacchella et al. 2016a,b; Tomassetti et al. 2016; Ceverino et al. 2016b,a; Mandelker et al. 2017; Dekel et al. 2020a,b). The simulations utilize the ART code (Kravtsov, Klypin & Khokhlov 1997; Kravtsov 2003; Ceverino & Klypin 2009), which follows the evolution of a gravitating N-body system and the Eulerian gas dynamics with an AMR maximum resolution of $17.5 - 35$ pc in physical units at all times. The dark-matter particle mass is $8.3 \times 10^4 M_{\odot}$ and the minimum mass of stellar particles is $10^3 M_{\odot}$. The code incorporates gas and metal cooling, UV-background photoionization and self-shielding in dense gas, stochastic star formation, stellar winds and metal enrichment, thermal feedback from supernovae (Ceverino, Dekel & Bournaud 2010), and feedback from radiation pressure. In

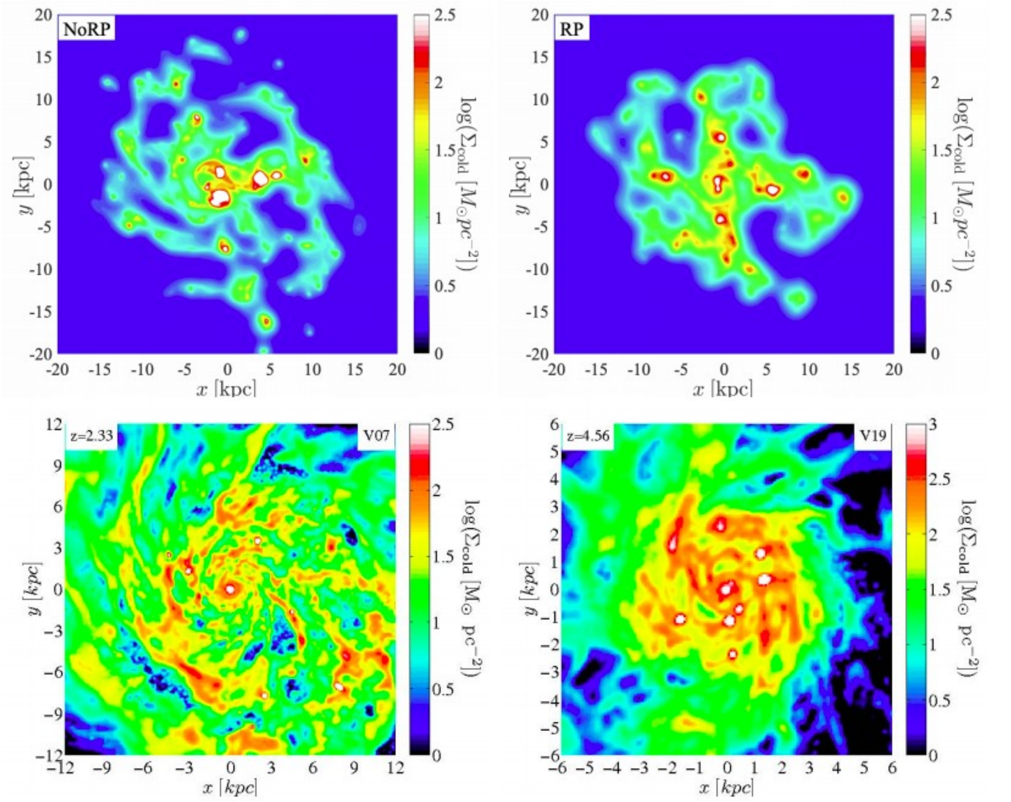

Figure 3. Face-on views of the surface gas density in simulated discs showing giant clumps. **Top:** Isolated simulations, NoRP and RP of G1 (Bournaud et al. 2014). Both show giant clumps, indicating less massive clumps when RP is incorporated. **Bottom:** Cosmological simulations, V07 at $z = 2.33$ (left) and V19 at $z = 4.56$ (right) from the `VELA-3` suite. Shown here is the surface density of the "cold" mass, comprised of cold gas ($T < 1.5 \times 10^4$ K) and young stars (< 100 Myr). The disc radii are $R_{\rm d} = 11.8$ and 3.2 kpc respectively. In both cases the disc half-thickness is $H_{\rm d} \sim R_{\rm d}/6$. The baryonic masses of the discs are $M_{\rm d}/(10^{10} M_{\odot}) \sim 3.50$ and 1.35, and the fractions of cold-mass are 28% and 33% respectively. Both discs show giant clumps with masses $M_{\rm c} > 10^8 M_{\odot}$. The gas density in and around the ~ 1 kpc vicinity of the clumps is similar in the isolated simulations and the cosmological simulations at $z \sim 2$, while the background density is higher in the cosmological simulations where gas is continuously accreted.

Abordagem analítica versus simulação

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Fonte: https://arxiv.org/pdf/2107.13561.pdf

5 SIMULATED CLUMPS VERSUS MODEL

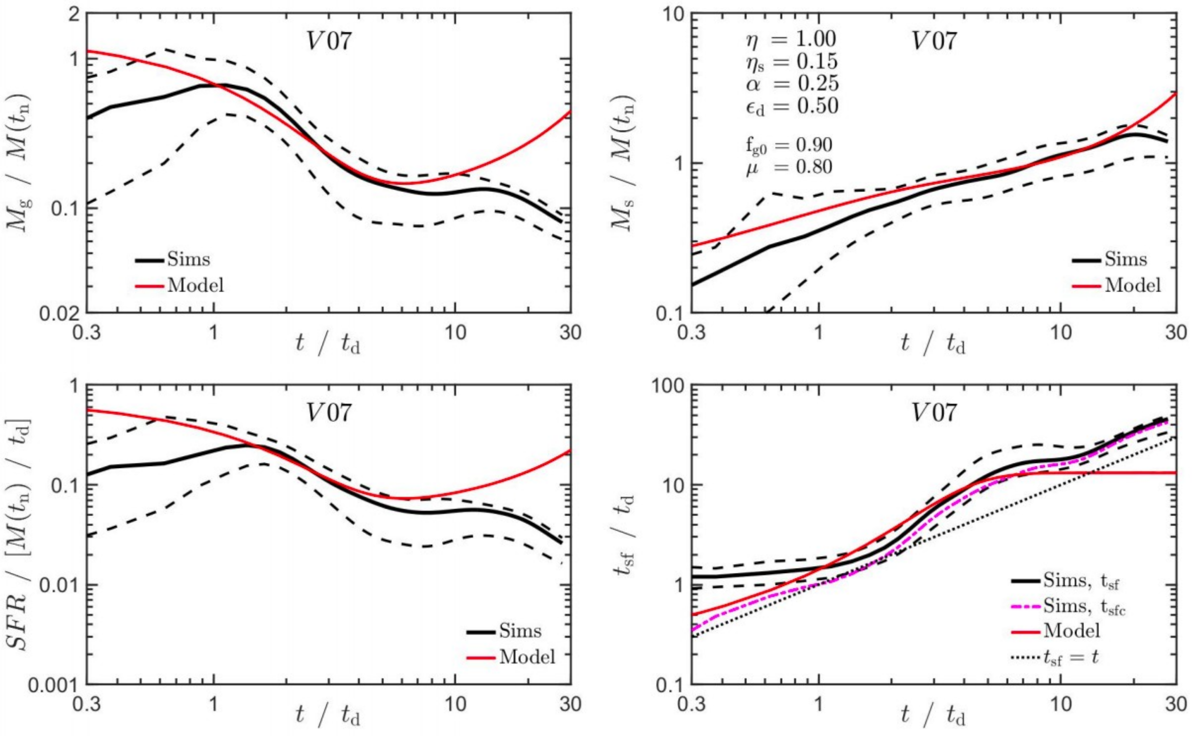

Figure 6. Evolution of simulated clump properties versus toy model, here for the cosmological galaxy V07 at $z = 2.5 - 1$. The details are the same as in Fig. 4, here with 37 clumps.

Abordagem analítica versus simulação

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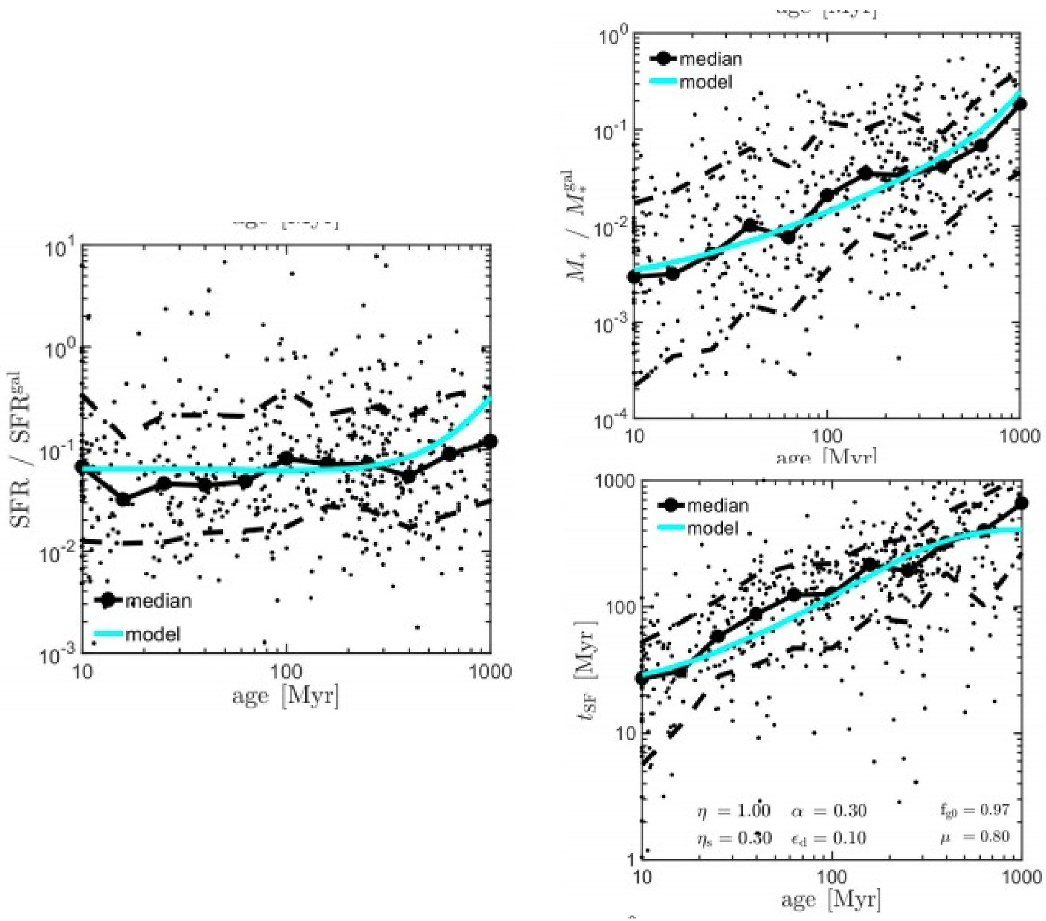
6 THEORY VERSUS OBSERVATIONS

6.1 Clumps in CANDELS

In Guo et al. (2018, hereafter G18), we have analyzed 3187 clumps identified in 1269 galaxies from the CANDELS/GOODS-S field in the redshift range $z = 0.5-3$, based on the sample described in Guo et al. (2015). The sample, clump detection and estimates of clump properties are described in these papers, while we bring only a very brief summary here.

For each galaxy, the stellar mass and SFR were determined by SED fitting, while the SFR was also determined directly from the UV flux. Star-forming galaxies were selected at $0.5 < z < 3$ to have global $M_s > 10^9 M_\odot$ and sSFR$> 10^{-1}$ Gyr^{-1}. An apparent magnitude cut of HF160W < 24.5 AB has been applied to ensure reliable morphology and size measurements. In order to be able to identify and measure clumps given the resolution, the sample has been limited to galaxies whose effective radii along the galaxy semi-major axis (SMA) is larger than 0.2”. To minimize the effect of dust extinction and

6.2 Simulated time vs age and distance



Vantagens de um protocolo padronizado para descrição de IBMs p. 116

- A standard protocol for the description of IBMs would make reading and understanding them easier because readers would be guided by their expectations.
- Gopen and Swan (1990) explain how understanding is facilitated when writers take readers' expectations into account: readers are better able to absorb information if it is provided in a familiar, meaningful structure.
- We conclude that what we badly need is a standard protocol for describing IBMs which combines two elements:
  - (1) a general structure for describing IBMs, thereby making a model's description independent of its specific structure, purpose and form of implementation (Grimm, 2002) and
  - (2) the language of mathematics, thereby clearly separating verbal considerations from a mathematical description of the equations, rules, and schedules that constitute the model.
- Such a protocol could, once widely used, guide both readers and writers of IBMs.

Protocolo ODD para descrição de modelos de Simulação IBM

- Visão geral
  - Propósito
  - Variáveis de estado e escalas
  - Processos e escalonamento
- Conceitos de Projeto
- Detalhes
  - Inicialização do modelo
  - Dados de Entrada
  - Submodelos

Overview	**Purpose**
	State variables and scales
	Process overview and scheduling
Design concepts	**Design concepts**
Details	**Initialization**
	Input
	Submodels

Protocolo ODD: Visão geral p. 127

- “After reading the overview it should be possible to write, in an object-oriented programming language, the skeleton of a program that implements the IBM described.
- This skeleton includes the declaration of all objects (classes) describing the models entities (different types of individuals or environments) and the scheduling of the model’s processes”

Protocolo ODD: Visão geral: Propósito

- The purpose of a model has to be stated first because without knowing it, readers cannot understand why some aspects of reality are included while others are ignored.
- Usually, the context and purpose of a model are provided in the introduction of an article, but it is nevertheless important to have a clear, concise and specific formulation of the model’s purpose because it provides a guide for what to expect in the model description that follows.
- Thus, this element informs about why you need to build a complex model, and what, in general and in particular, you are going to do with your model.

Protocolo ODD: Visão geral: Variáveis de estado e escalas p. 117

- What is the structure of the model system?
- For example, what kind of low-level entities (e.g., individuals, habitat units) are described in the model?
- How are they described?
- What hierarchical levels exist?
- How are the abiotic and biotic environments described?
- What is the temporal and spatial resolution and extent of the model system?

Protocolo ODD: Visão geral: Variáveis de estado p. 117

- The term ‘state variables’ refers to low-level variables that characterize the low-level entities of the model, i.e. individuals or habitat units. For example, individuals might be characterized by a number of characteristics: age, sex, social rank, location, parents; habitat units might be characterized by location, soil type, predation risk (for a certain species), percentage cover.
- It is important not to confuse low-level state variables with auxiliary, or aggregated, variables, such as population size or average food density in a given area. Auxiliary variables contain information that is deduced from low-level entities and their low-level state variables. Population size, for example, is simply the number of individuals; age structure is a histogram taken from the age of all individuals; average food density is the average of the amount of food in every habitat unit in a given region.
- In contrast, low-level state variables cannot be deduced from other low-level state variables, because they are elementary properties of model entities.

Protocolo ODD: Visão geral: Escalas p. 117

- Finally, in addition to the state variables, the scales addressed by the model should be stated, i.e. length of time steps and time horizon, size of habitat cells (if the model is grid-based), and extent of the model world (if the model is spatially explicit).
- The reason why these scales have been selected should briefly be explained, because choosing the scale is a fundamental decision determining the design of the entire model.
- The dimensions must be clearly defined for all parameters and variables in the tables, to avoid confusion and inconsistencies and allow model reproduction.
- With spatially explicit models that include spatial heterogeneity, a figure representing the model area in a typical configuration can be useful.

Protocolo ODD: Visão geral: **Processos** e escalonamento

- To understand an IBM, we must know which environmental and individual processes are built into the model; examples are food production, feeding, growth, movement, mortality, reproduction, disturbance events, and management.
- At this stage, a verbal, conceptual description of each process and its effects is sufficient because the main purpose of this element of ODD is to give a concise overview.
- If the number of processes included in the model is large, a table listing the processes might be useful.

Protocolo ODD: Visão geral: Processos e **escalonamento**

- In addition, the scheduling of the model processes should be described. This deals with the order of the processes and, in turn, the order in which the state variables are updated. More specific questions include:
- How is time modelled in the IBM—using discrete time steps, continuous time, or both?
- Is dynamic scheduling used for events that happen quickly compared to the model's time step and are highly dependent on execution order?
- What model processes or events are grouped into actions that are executed together?
- Do these actions produce synchronous or asynchronous updating of the state variables?
- How are actions that actually happen concurrently in nature executed in the model?
- What actions are on a fixed schedule, and in what order?
- Are some actions executed in random order?
- What is the basis for these scheduling decisions?

Protocolo ODD: Conceitos de Projeto

- “The block or element “Design concepts” does not describe the model itself, but rather describes the general concepts underlying the design of the model.”
- “The purpose of this element of the protocol is to link model design to general concepts identified in the field of Complex Adaptive Systems.”
- “These concepts include questions about
  - emergence,
  - the type of interactions among individuals,
  - whether individuals consider predictions about future conditions, or
  - why and how stochasticity [property of being well described by a random probability distribution] is considered.”

Protocolo ODD: Checklist de conceitos necessários ao projeto de uma Simulação IBM

1. Emergence: Which system-level phenomena truly emerge from individual traits, and which phenomena are merely imposed?

2. Adaptation: What adaptive traits do the model individuals have which directly or indirectly can improve their potential fitness, in response to changes in themselves or their environment?

3. Fitness: Is fitness-seeking modelled explicitly or implicitly? If explicitly, how do individuals calculate fitness (i.e., what is their fitness measure)? In agent-based models that do not address animals or plants, instead of fitness other “objectives” of the agents should be considered here (e.g. economic revenue, pollution control).

4. Prediction: In estimating future consequences of their decisions, how do individuals predict the future conditions they will experience?

5. Sensing: What internal and environmental state variables are individuals assumed to sense or “know” and consider in their adaptive decisions?

6. Interaction: What kinds of interactions among individuals are assumed?

7. Stochasticity: Is stochasticicity part of the model? What are the reasons?

8. Collectives: Are individuals grouped into some kind of collective, e.g. a social group?

9. Observation: How are data collected from the IBM for testing, understanding, and analyzing it?

Protocolo ODD: Detalhes
p. 117

- “Includes three elements (initialization, input, submodels) that present the details that were omitted in the overview.”
- “In particular, the submodels implementing the model’s processes are described in detail.”
- “All information required to completely re-implement the model and run the baseline simulations should be provided here.”

Protocolo ODD: Detalhes: Inicialização

- How are the environment and the individuals created at the start of a simulation run, i.e. what are the initial values of the state variables?
- Is initialization always the same, or was it varied among simulations?
- Were the initial values chosen arbitrarily or based on data? References to those data should be provided.
- Communicating how IBMs are initialized can be important if peers want to re-implement the IBM and reproduce the simulation experiments reported.

Protocolo ODD: Detalhes: Dados de Entrada

- The dynamics of many IBMs are driven by some environmental conditions which change over space and time. A typical example is precipitation, which may vary over time (seasons, years) and space (different spatial patterns of rainfall in different regions), and management, e.g. harvesting regimes (management might also be addressed in the section “simulation experiments”, which usually will follow the model description).
- All these environmental conditions are “input”, i.e. imposed dynamics of certain state variables.
- To really achieve full reproducibility it might be necessary to provide (in online archives) the input files that you used yourself, including even the random number used as seed.

Protocolo ODD: Detalhes: Submodelos

- All submodels representing the processes listed in “Process overview and scales” are presented and explained in detail, including the parameterization of the model.
- We propose that two versions of the detailed model description be written:
  - The mathematical “skeleton” of the model. This skeleton consists of the model equations and rules and one or more tables presenting the model parameters and their dimensions. Verbal explanations of the equations and rules should be kept to a minimum: parameters have of course to be explained, but longer explanations of why this specific model formulation was chosen, how the parameters were determined, etc., do not belong here. If the list of equations and rules is too long, it should be presented in an Online Appendix.
  - A full model description. This version has exactly the same structure as the “skeleton” (i.e., the same subtitles and equation numbers), but now each equation and parameter is verbally explained in full detail and deals with questions such as: What specific assumptions are underlying the equations and rules? How were parameter values chosen? How were submodels tested and calibrated? Ideally, the two versions of the detailed model description could be presented in the same document, with the more detailed verbal descriptions hidden to readers in version one but visible in version two. (This technique is partly used in the HTML model description of Deutschman et al. (1997) where readers can chose links providing more detailed information.)

Exemplo

Protocolo ODD: Exemplo: Visão geral: Propósito

The purpose of the model is to understand how the social behaviour of the marmots – in particular territoriality, reproductive suppression, and hibernation as a group – affects population dynamics and in particular extinction risk if populations are small.

Protocolo ODD: Computação Experimental: Visão geral: Propósito

- 1ª versão
  - O propósito do modelo de simulação é compreender como o comportamento social dos cientistas – em particular envolvimento em projetos, filiação a países, organizações e comunidades científicas, atuação em áreas das ciências humanas ou naturais, culturais ou tecnológicas, participação em atividades colaterais de ensino, pesquisa e empreendedorismo – afeta o seu desempenho, em particular a produtividade científica, mensurada por índices de impacto.
- 2ª versão (limitada pela indisponibilidade de dados empíricos)
  -

Protocolo ODD: Exemplo: Visão geral: Variáveis de estado e escalas p. 117

The model comprises four hierarchical levels: individual, territory, (meta)population, and environment. Individuals are characterized by the state variables: identity number, age, sex, identity of the territory where the individual lives, and social rank. Newborns have the additional state variable weaning weight, which affects their mortality. Individuals which have not completed their first winter are referred to as juveniles; 1-year-olds as yearlings, and all others as adults. Apart from this, social rank is the main attribute which tells the difference between dominant and subdominant adults (Table 1).

Protocolo ODD: Exemplo: Visão geral: Variáveis de estado e escalas p. 117

A territory may be occupied by a social group of marmots and contains one hibernaculum used by this group during winter. A territory is characterized by the state variables: identity number, the number and list of individuals present, and its quality. If the number of individuals is zero, the territory is referred to as 'empty', i.e. space which has become vacant due to the extinction of a social group. Thus, territories may be recolonized just like empty patches in metapopulations. 'Quality' is an attribute characterizing habitat heterogeneity with respect to the harshness of overwintering conditions, indicated by the date in spring when a territory becomes snow-free.

Protocolo ODD: Exemplo: Visão geral: Variáveis de estado e escalas p. 117

The population is composed of several territories or social groups, respectively. Populations are characterized by size, the number of social groups, and the number and list of territories. In addition, a “floater pool” keeps track of both all subdominants which have left their home territory and dominants which have been evicted. The spatial structure is taken into account by specifying the linkages to neighbouring territories. A neighbouring territory is defined as a territory within the distance of 500 m. The number of linkages may vary between zero and six (Fig. 2). Clusters of neighbouring territories compose a local metapopulation. Several clusters make up the regional metapopulation of the alpine marmot (Fig. 2). As distances between clusters are greater than 500 m, only dispersing subdominants will cross this distance. On this spatial scale beyond 500 m the model is not spatially explicit but the dispersers may reach any cluster of territories within the model area. This restricts the extent of the area that can be described by the model to several square kilometres.

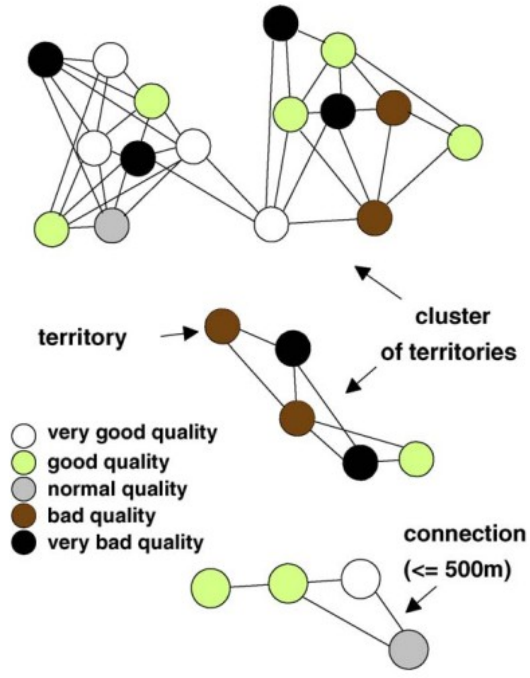


Fig. 2 – Spatial arrangement of territories in the model. Territories which are closer than 500 m to each other are linked by lines, indicating the chance of subdominants recolonizing vacant dominant positions within this neighbourhood without undertaking long-distance dispersal. The different grey scales of the territories indicate different habitat qualities of the territories (from Grimm et al., 2003, after Dorndorf, 1999).

Protocolo ODD: Exemplo: Visão geral: Variáveis de estado e escalas p. 117

The highest hierarchical level in the model is the abiotic environment and its fluctuations. Since the severity of winter, indicated by the date when territories become snow-free, is the most important aspect in the life of marmots, the abiotic environment in the model is characterized by this date. The date when a territory becomes snow-free is referred to as 'winter strength'; it is drawn from a normal distribution and modulated by the quality of the territories.

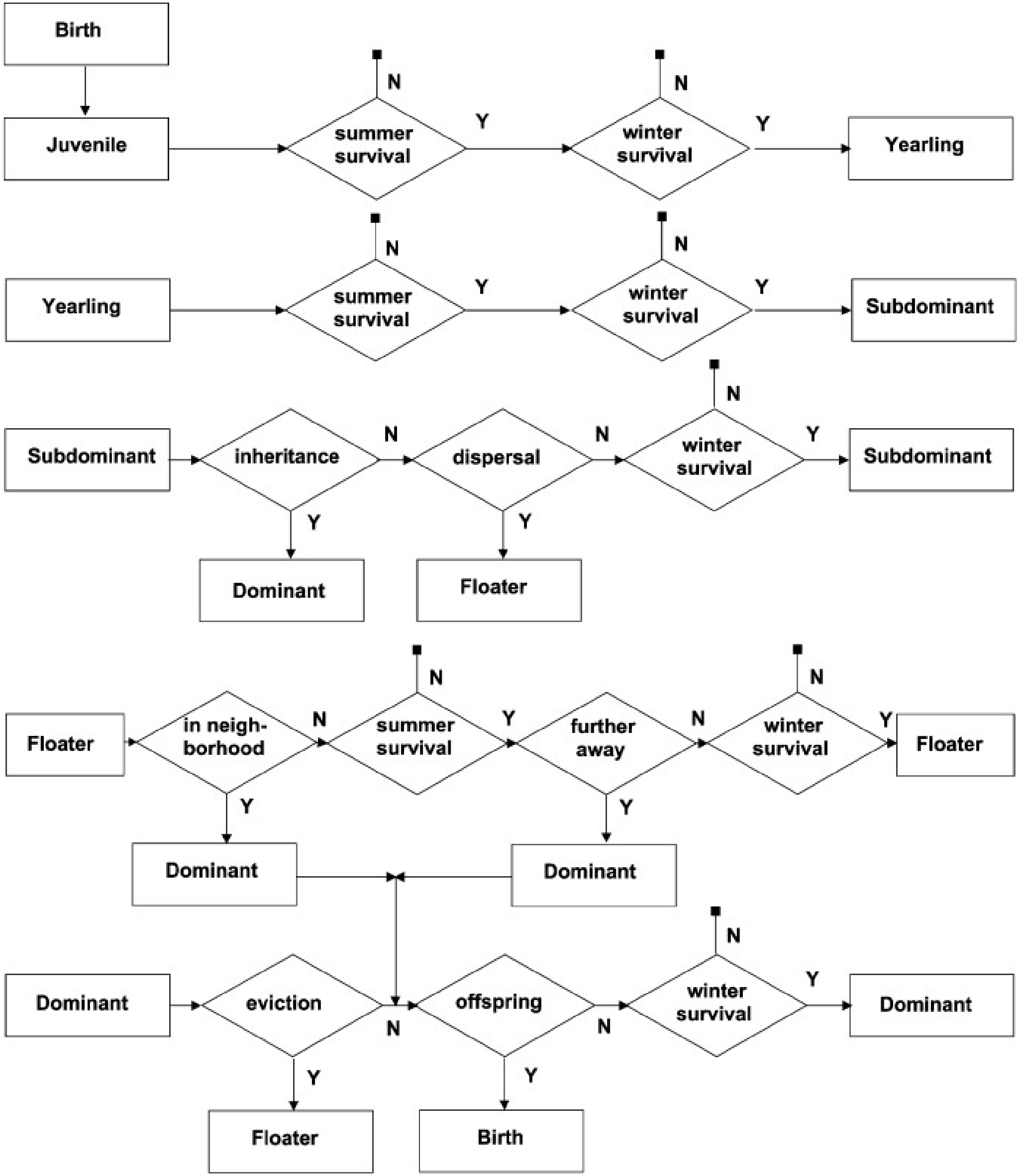
Protocolo ODD: Exemplo: Visão geral: Variáveis de estado

Protocolo ODD: Exemplo: Visão geral: Escalas

Protocolo ODD: Exemplo: Visão geral: **Processos** e escalonamento

The model proceeds in annual time steps. Within each year or time step, seven modules or phases are processed in the following order: winter mortality, eviction, inheritance, dispersal, re-colonization of vacant dominant positions, reproduction, and summer mortality. Within each module, individuals and territories are processed in a random order. The individuals life cycle is depicted in Fig. 3.

Protocolo ODD: Exemplo: Visão geral: Processos e escalonamento



Protocolo ODD: Exemplo: Visão geral: Processos e **escalonamento**

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4. Prediction: In estimating future consequences of their decisions, how do individuals predict the future conditions they will experience?

5. Sensing: What internal and environmental state variables are individuals assumed to sense or “know” and consider in their adaptive decisions?

6. Interaction: What kinds of interactions among individuals are assumed?

7. Stochasticity: Is stochasticicity part of the model? What are the reasons?

8. Collectives: Are individuals grouped into some kind of collective, e.g. a social group?

9. Observation: How are data collected from the IBM for testing, understanding, and analyzing it?

Protocolo ODD: Exemplo: Conceitos de Projeto

Emergence: Population dynamics emerge from the behaviour of the individuals, but the individual's life cycle and behaviour are entirely represented by empirical rules describing, for example, mortality and dispersal rates as probabilities. Adaptation and fitness-seeking are thus not modelled explicitly, but are included in the empirical rules.

Protocolo ODD: Exemplo: Conceitos de Projeto

Sensing: Individuals are assumed to know their own sex, age, and social rank so that they apply, for example, their age-specific dispersal probabilities.

Protocolo ODD: Exemplo: Conceitos de Projeto

Interaction: Three types of interactions are modelled implicitly: winter mortality decreases with group size, alpha individuals suppress reproduction of subdominants, and after changes in the alpha male position in the current year, the alpha female does not reproduce. One interaction is modelled explicitly: subdominants and individuals from the floater pool can try to evict alpha individuals.

Protocolo ODD: Exemplo: Conceitos de Projeto

Stochasticity: All demographic and behavioural parameters are interpreted as probabilities, or are drawn from empirical probability distributions. This was done to include demographic noise and because the focus of the model is on population-level phenomena, not on individual behaviour. Winter strength was taken from a truncated normal distribution in order to include environmental noise (i.e., variation of the population's growth rate driven by fluctuations of abiotic conditions). Likewise, habitat quality was taken from a truncated normal distribution in order to include spatial heterogeneity.

Protocolo ODD: Exemplo: Conceitos de Projeto

Observation: For model testing, the spatial distribution of the individuals was observed process by process. For model analysis, only population-level variables were recorded, i.e. group size distribution, population size over time, and time to extinction (using the "$\ln(1-P_0)$ plot" of Grimm and Wissel, 2004).

Protocolo ODD: Exemplo: Detalhes

Protocolo ODD: Exemplo: Detalhes: Inicialização

Each territory was initially occupied with a 5-year-old couple of dominants and both a 1-year-old male and female sub-dominant. The evaluation of each simulation run started in the first year when the number of model adults was equal to the number of adults observed in the first year of the field study.

Protocolo ODD: Exemplo: Detalhes: Dados de Entrada

In general model analysis, each year winter strength is drawn from a normal distribution with an empirically determined mean and standard deviation (mean = 117 days of the year for territories in the study area, s = 10.2 days). This overall winter strength is modified by differences in overwintering conditions among territories, i.e., from a normal distribution with a mean of zero and a standard deviation of 8.4 days. This means that territories which have a higher quality than the mean become snow-free a certain number of days earlier than specified by the overall winter strength, whereas territories of lower quality become snow-free later.

Protocolo ODD: Exemplo: Detalhes: Submodelos

Winter mortality: For dominant marmots, winter mortality – interpreted as the probability of dying in a certain winter – is determined from the long-term data set by logistic regression:

$$P_{ter} = [1 + \exp(6.82 - 0.286A - 0.028WS + 0.395SUBY)]^{-1} \quad (1)$$

where A is the age, WS winter strength, and SUBY is the number of subdominants (including yearlings) present in a group. Eq. (1) states that the winter mortality of dominants increases with the severity of overwintering conditions and with age, but decreases with the number of subdominants and yearlings.

Similarly, winter mortality for subdominants (including yearlings) is:

$$P_{sub} = [1 + \exp(7.545 - 0.038WS)]^{-1} \quad (2)$$

For juveniles, we found in addition a significant influence of weaning weight on winter mortality:

$$P_{new} = [1 + \exp(-1.014 - 0.024WS + 0.008WW + 0.613SUB)]^{-1} \quad (3)$$

with WW being the weaning weight (see below, *Reproduction*) and SUB the number of subdominants (excluding yearlings).

Protocolo ODD: Exemplo: Detalhes: Submodelos

Dispersal: Most of the subdominants willing to disperse leave their home territory in spring. The probability of leaving depends on age and is directly taken from Table 2. Dispersed animals are compiled in a list called the “floater pool”. This list is used to handle the assignment of free dominant positions to floaters. Note that the floater pool contains both true floaters which disperse beyond 500 m and are subject to dispersal mortality during summer, and animals which will take over a dominant position in the neighbourhood.

Recolonization: In the model, recolonization is implemented by the following suite of rules. The first rule decides with a probability of $R_N = 0.5$ whether a vacant dominant position is reoccupied by a marmot that comes from a neighbouring territory. If this is the case, the floater pool is searched (in a random order) for such an animal, and if no animal is found the dominant position remains vacant. After repeating this procedure for each vacant dominant position, the remaining animals in the floater pool are treated as true floaters and have a dispersal mortality of $P_D = 0.3$, i.e. about 30% of the remaining floaters die before the next model rules are applied.

Protocolo ODD: Exemplo: Detalhes: Submodelos

Reproduction: Only when a dominant male and female are present in a territory reproduction can take place. The probability of a dominant female having offspring is 0.64 (Hackländer and Arnold, 1999). The mean litter size (L) is 3.3 and standard deviation is 1.43. The mean weaning weight (WW_{mean}) is 536 g (S.D. = 126.3 g) but decreases with litter size. Therefore a regression model is used to assess a mean weaning weight depending on litter size L ($WW_{mean} = 680.23 - 35.24L$, $R^2 = 0.143$, $P < 0.001$). In the model, litter size and weaning weight are drawn from normal distributions (in the case of litter size, discretized and truncated to the interval [1,6]) with the means and standard deviations specified. The sex of offspring is determined by chance with a bias of 0.58 towards males. We assume that no reproduction occurs if the holder of a male dominant position has changed during the current year.

Protocolo ODD: Exemplo: Detalhes: Submodelos

Summer mortality: Summer mortality rates are only known from the field for juveniles and yearlings. Summer mortality of resident adults is low but hard to quantify. The summer mortality of adults is thus indirectly and implicitly taken into account in the probabilities of eviction and dispersal mortality. Newborns and yearlings die during summer with a probability of 0.11 and 0.07, respectively.