Using Statistical Model Checking in a Process for Evaluating and Calibrating a Model of Tropical Forest Dynamics

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Outline

- Studying a Forest Model
  - Forest of Paracou
  - A Forest Model
  - A Process to Evaluate and Calibrate it
- Some challenges, experiments and questions as a newcomer
  - on the models and properties involved
  - on the process

Amazonian forest

research fields : biodiversity, forest dynamics and climate changes

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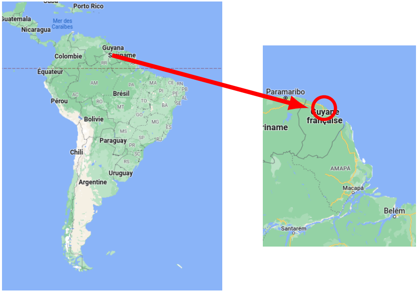
CIRAD Research Center In French Guyana



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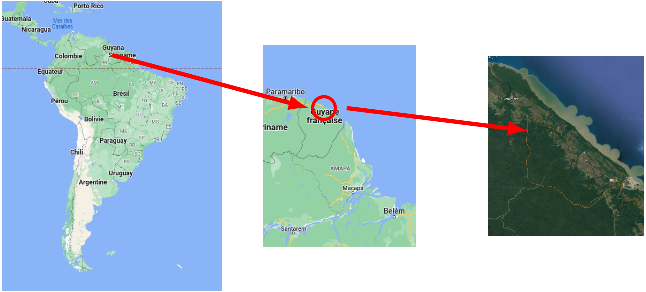

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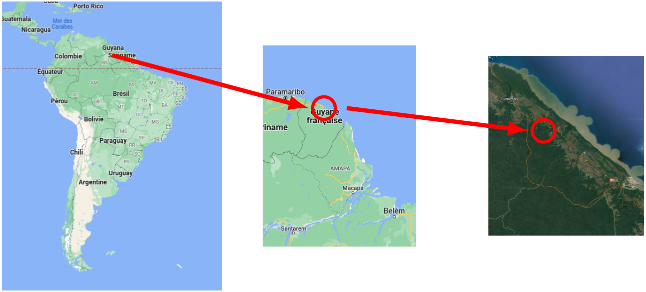

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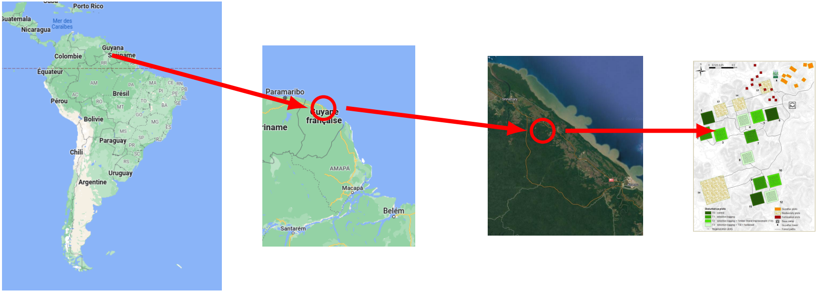

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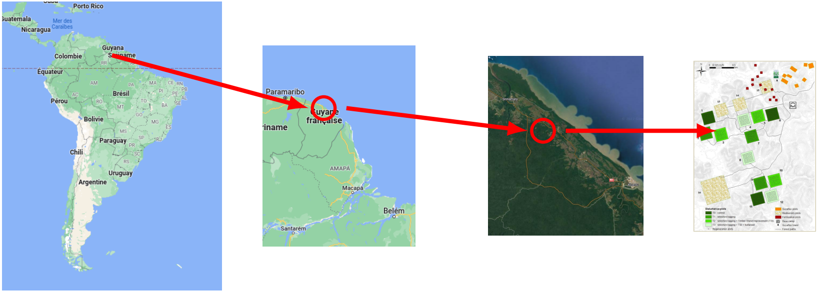
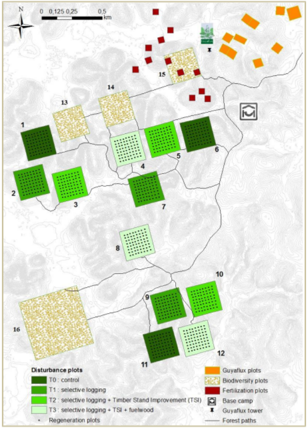


research fields : biodiversity, forest dynamics and climate changes

The plots



- 16 permanent plots (fifteen 6.25 ha plus one 25 ha) have been censused every 1-2 years for more than 35 years.

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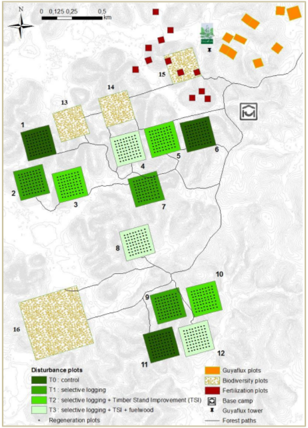

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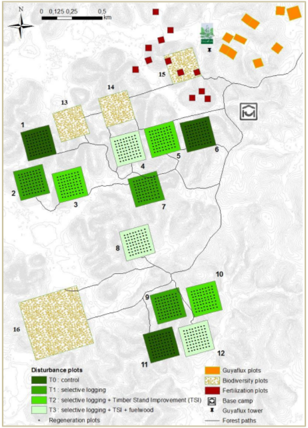

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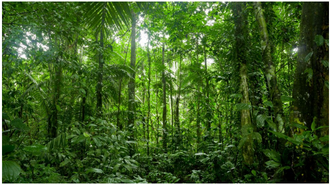

https ://paracou.cirad.fr/website/miscellaneous/pretty-pictures/inventory-measurement

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- Each plot contains about 50 different Families, 150-200 species and 5-8k trees
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some regions not always accessible

Decades of Data

More than just counting trees

- ID
- geolocalisation
- family, genus and species when possible
- circumference

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around 80-120 k entries for each plot

Forest	Plot	PlotArea	SubPlot	TreeF	idTree	Xfield	Yfield	Xutm	Yutm	Lat	Lon	Family	Genus	Species	BotaSource	Bo	idVern	VernName	Comm	CensusYear	CensusDate
Paracou	4	6,25	1	1	89069	0,5	125,5	285844,84375	582934,625	5,27080011367798	-52,932300567627	Sapotaceae	Pradosia	cochlearia	Bota	4	402	kimboto	0	1984	1984-08-01
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Paracou	4	6,25	1	1	89069	0,5	125,5	285844,84375	582934,625	5,27080011367798	-52,932300567627	Sapotaceae	Pradosia	cochlearia	Bota	4	402	kimboto	0	1999	1999-08-26
Paracou	4	6,25	1	1	89069	0,5	125,5	285844,84375	582934,625	5,27080011367798	-52,932300567627	Sapotaceae	Pradosia	cochlearia	Bota	4	402	kimboto	0	2001	2001-10-31
Paracou	4	6,25	1	1	89069	0,5	125,5	285844,84375	582934,625	5,27080011367798	-52,932300567627	Sapotaceae	Pradosia	cochlearia	Bota	4	402	kimboto	0	2003	2003-08-11
Paracou	4	6,25	1	1	89069	0,5	125,5	285844,84375	582934,625	5,27080011367798	-52,932300567627	Sapotaceae	Pradosia	cochlearia	Bota	4	402	kimboto	0	2005	2005-11-24
Paracou	4	6,25	1	1	89069	0,5	125,5	285844,84375	582934,625	5,27080011367798	-52,932300567627	Sapotaceae	Pradosia	cochlearia	Bota	4	402	kimboto	0	2007	2007-08-05
Paracou	4	6,25	1	1	89069	0,5	125,5	285844,84375	582934,625	5,27080011367798	-52,932300567627	Sapotaceae	Pradosia	cochlearia	Bota	4	402	kimboto	0	2009	2009-11-19
Paracou	4	6,25	1	1	89069	0,5	125,5	285844,84375	582934,625	5,27080011367798	-52,932300567627	Sapotaceae	Pradosia	cochlearia	Bota	4	402	kimboto	0	2011	2011-11-09
Paracou	4	6,25	1	1	89069	0,5	125,5	285844,84375	582934,625	5,27080011367798	-52,932300567627	Sapotaceae	Pradosia	cochlearia	Bota	4	402	kimboto	0	2013	2013-09-01
Paracou	4	6,25	1	1	89069	0,5	125,5	285844,84375	582934,625	5,27080011367798	-52,932300567627	Sapotaceae	Pradosia	cochlearia	Bota	4	402	kimboto	0	2015	2015-12-01
Paracou	4	6,25	1	1	89069	0,5	125,5	285844,84375	582934,625	5,27080011367798	-52,932300567627	Sapotaceae	Pradosia	cochlearia	Bota	4	402	kimboto	0	2017	2017-10-04
Paracou	4	6,25	1	1	89069	0,5	125,5	285844,84375	582934,625	5,27080011367798	-52,932300567627	Sapotaceae	Pradosia	cochlearia	Bota	4	402	kimboto	0	2019	2019-09-12
Paracou	4	6,25	1	2	89070	2	125,5	285846,28125	582935	5,27080011367798	-52,932300567627	Lecythidaceae	Lecythis	persistens	Bota	4	404	maho rouge	0	1984	1984-08-01
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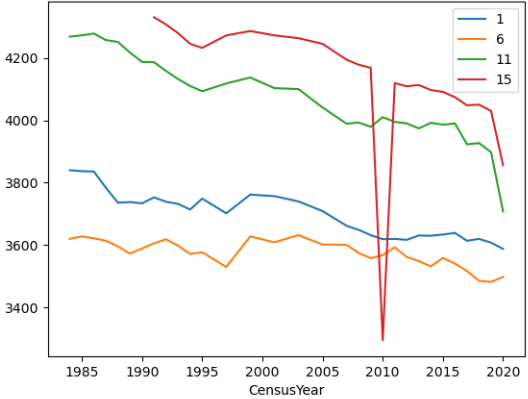
Paracou	4	6,25	1	2	89070	2	125,5	285846,28125	582935	5,27080011367798	-52,932300567627	Lecythidaceae	Lecythis	persistens	Bota	4	404	maho rouge	0	2001	2001-10-31

Number of trees

- Number of trees : reference plots (No logging)



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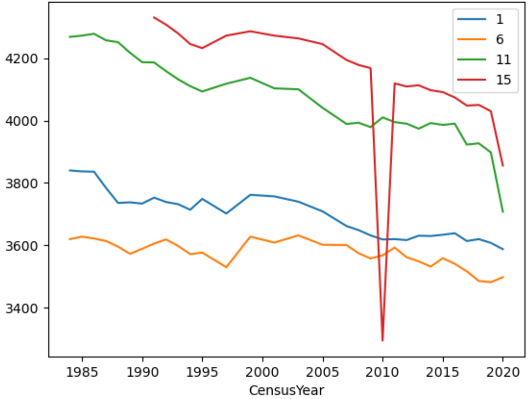

plot 15 wasn't always fully reachable

Number of trees : The case of plot 15

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A tree is alive between any two dates where it has been noted alive

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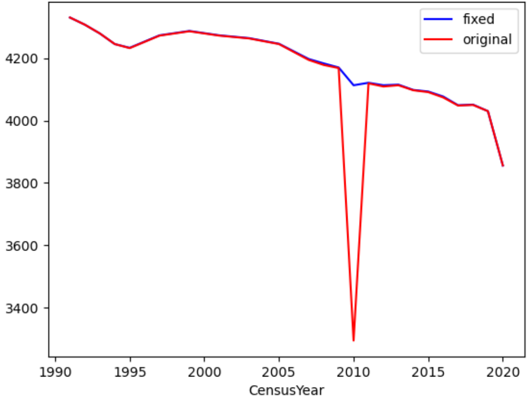

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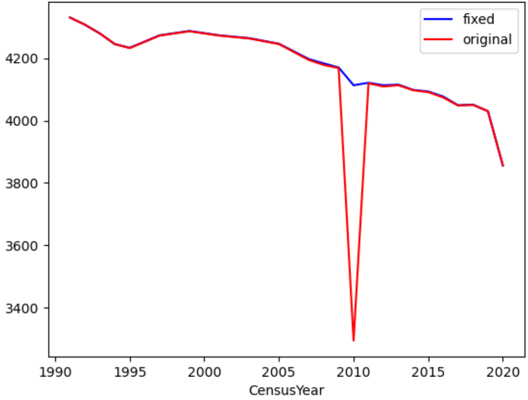

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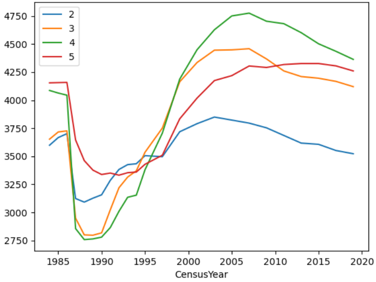
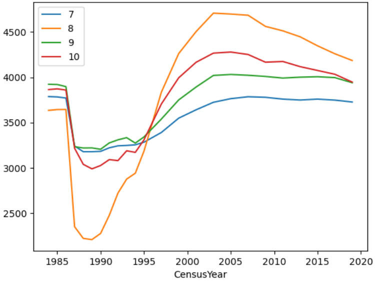
Correction under 1‰ for the other plots

Number of trees

- Number of trees in plots where logging occurred.





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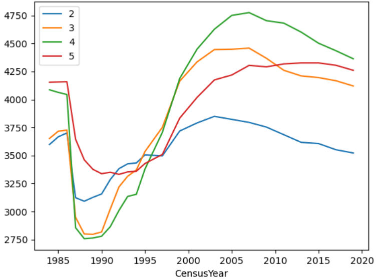

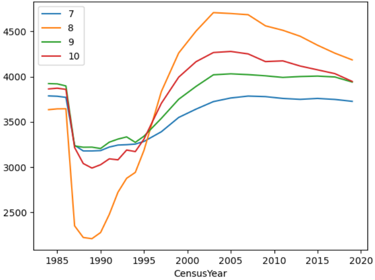

Different recovery rates, sometimes failing to reach the starting point

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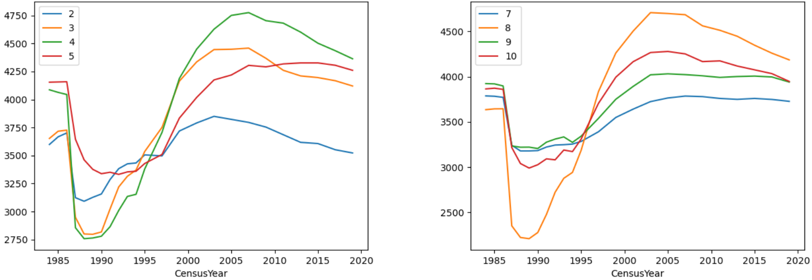

Different recovery rates, sometimes failing to reach the starting point
The regrowth is what we want to model.

Model Properties

Properties we want for the model

- close enough to the data
- as few parameters as possible
- preferably identifiable parameters

- Usable to simulate perturbations

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▶ Usable to simulate perturbations

Problem

relevant models in the litterature are age-structured :
Young trees vs Mature trees which can produce seeds

First Model

Antonovsky and Korzukhin (1990) :

$u \rightsquigarrow$ young trees, $v \rightsquigarrow$ mature trees

$$\begin{cases} \dot{u} = \rho v - \gamma(v)u - fu, \\ \dot{v} = fu - hv. \end{cases}$$

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$$\begin{cases} \dot{u} = \rho v - \gamma(v)u - fu, \\ \dot{v} = fu - hv. \end{cases}$$

$$\begin{array}{rcl} \rho & \rightsquigarrow & \text{recruitment (birth) rate,} \\ f & \rightsquigarrow & \text{aging rate,} \\ h & \rightsquigarrow & \text{mortality,} \\ \gamma(v) & \rightsquigarrow & \text{competition} \\ \\ \gamma(v) & = & a(v-b)^2 + c. \end{array}$$

Widely studied and the basis of many forest dynamics models

Three parameter regimes

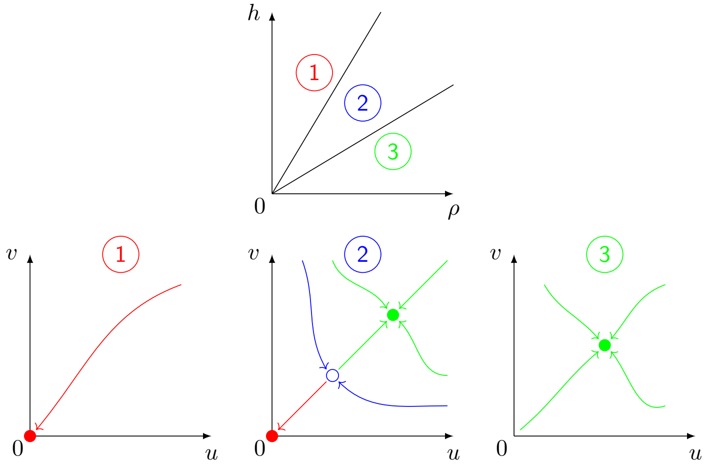
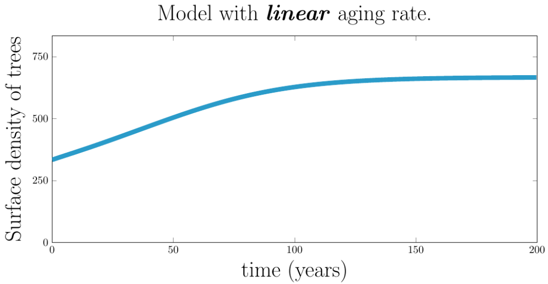


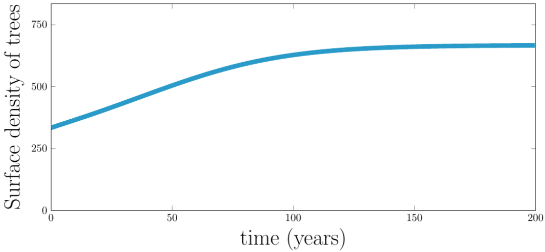
Figure – Three possible dynamics : dying forest, healthy forest or coexistence between persistence and extinction

Overall shape for most parameter values



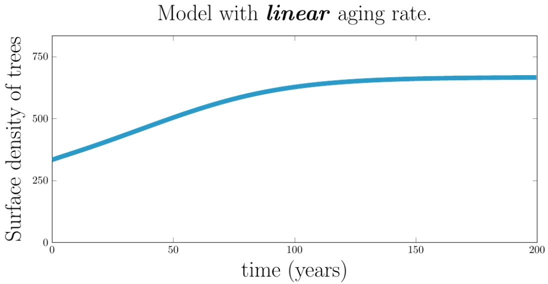
Overall shape for most parameter values

Model with ***linear*** aging rate.



- The oscillation seen post logging is absent using the linear aging term $\pm fu$

Overall shape for most parameter values



- The oscillation seen post logging is absent using the linear aging term $\pm fu$
- Intuition : reaching maturity is also a kind of competition
  - bounded by a maximal tree density
  - fiercer among youngs

Tuning the aging term

- Replacing $\pm fu$ with

$$fu \times v \times (T_{max} - (u + v)).$$

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Tuning the aging term

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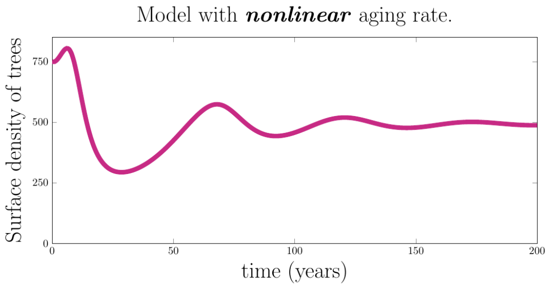
- $\times (T_{max} - (u + v)) \rightsquigarrow$ maturing is bounded by the maximum density.



Evaluating the model

Now that we have a more promising candidate model, we want to see how it behaves :

- can it fit the data ?
- can common (or close enough) values of parameters fit all the plots ?
- can we determine regions of interest in the parameter space ?
- can we observe strong correlation between parameters (hint at simplification)

Fitting the data - Properties and measure

Qualitative

the simulation stays within $D\%$ of the data, except for a maximum of K outliers.

Quantitative

average distance to the data (as %), number of outliers

Defining the parameter space

Finding a plausible range for each parameter.

- bounds can be obvious (no negative mortality rate)
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- detecting False positives coming from a broad property that is not discriminating enough

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Finding a plausible range for each parameter.

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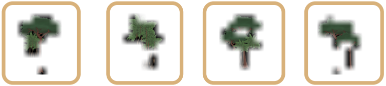
Then we need to discretize the space

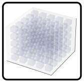
Evaluation Process

Model

$$\dot{u} = \varphi(u, v)$$
$$\dot{v} = \psi(u, v)$$

Data



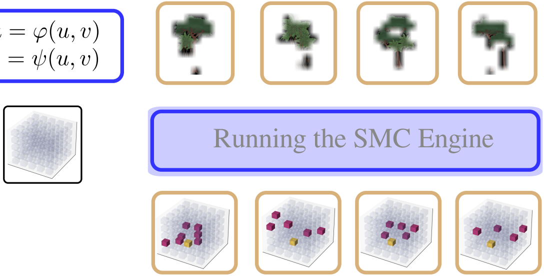


Evaluation Process

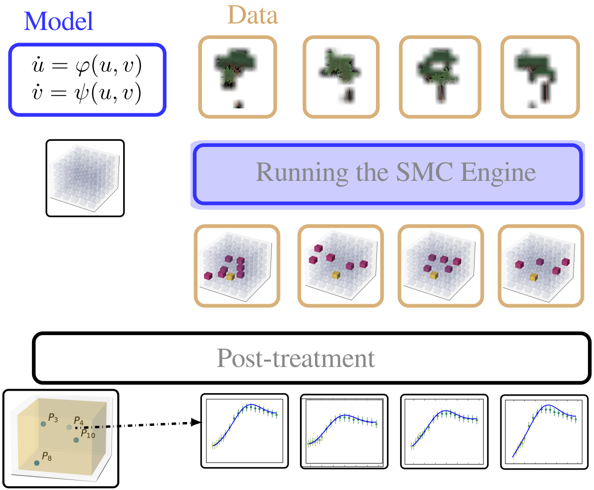
Model

$$\dot{u} = \varphi(u, v)$$
$$\dot{v} = \psi(u, v)$$

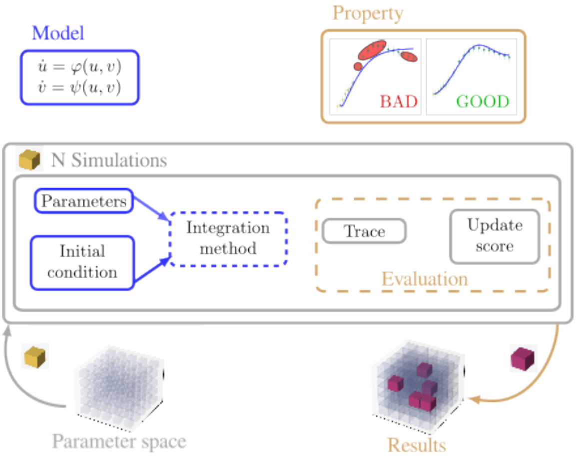
Data



Evaluation Process

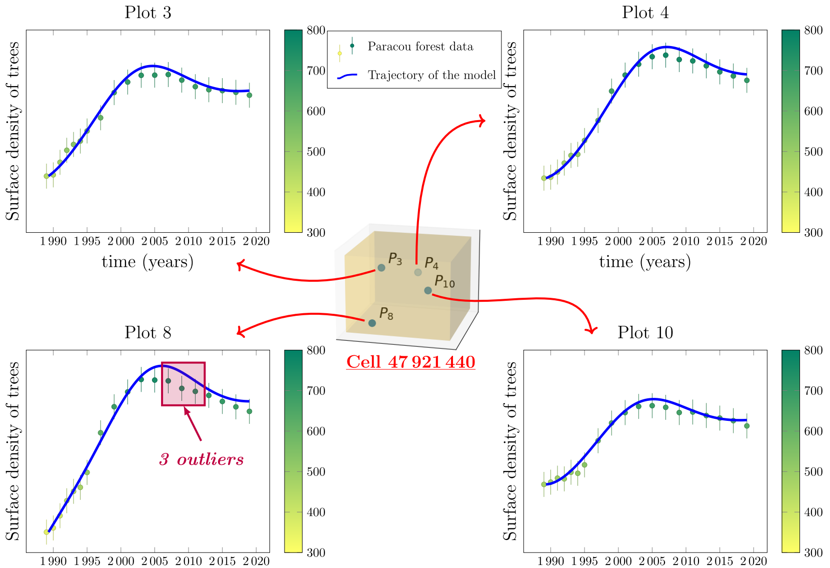


Evaluation Process - SMC

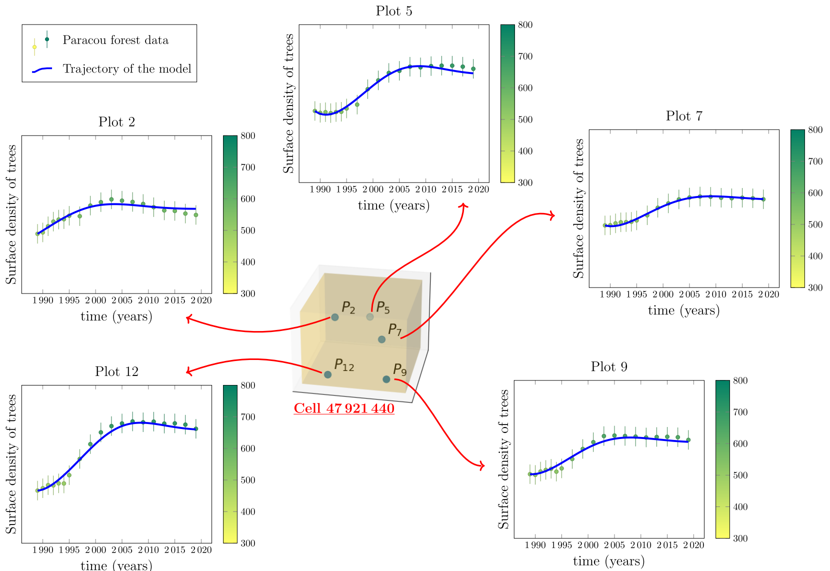


N is determined based on precision guarantees.
score is the % of good simulations

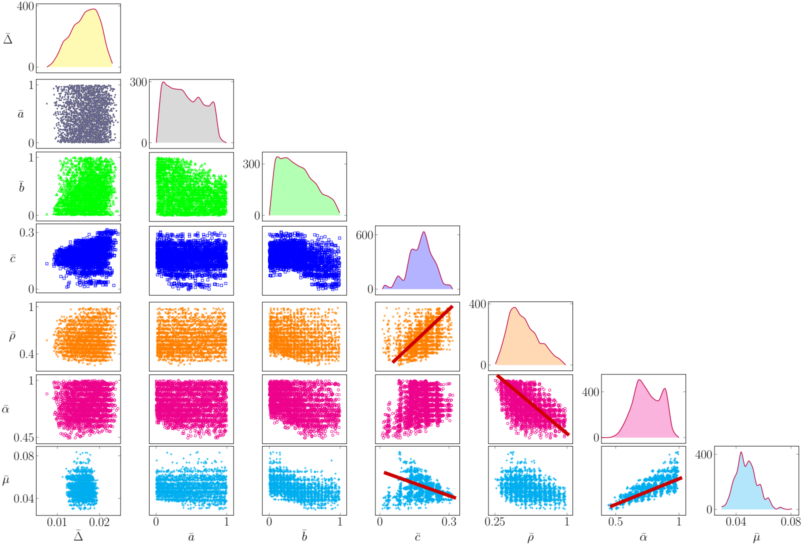
Results on the base plots



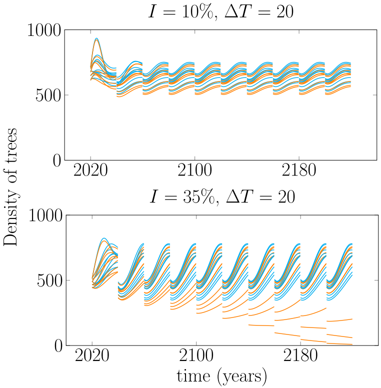
Results on the control plots

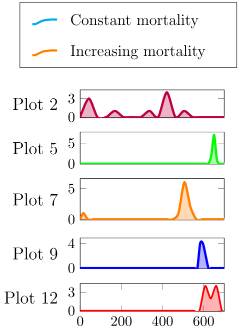


The overall picture



Example of applications





Distributions of the final densities of each plot

First Impressions

Coming from Sofware Engineering Verification

In my previous world, reality was a simulation of the models, because most of SE models are more like blueprints. Especially in correct by construction software.

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"Real world models" are different beasts.

Properties are complex as well

My preliminary conclusion

The fitting property inside a biologist's brain is complex and somehow unpredictable

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distance and outliers are only a part of the equation.
There's something about shape , but how to capture it efficiently ?

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  - could Young/Old distribution be inferred from the data ?
  - use GPS data to get finer grained info about density ?
- Even params that are supposed to be reflected in the data (birthrate) won't be a perfect fit (variability +abstraction). how far can they go from their real counterparts ? They should be correlated enough to let us make predictions

First impression

The process from a user perspective

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5. notice that you've mistyped a value in the parameter ranges or a threshold in the property
6. sigh and start again

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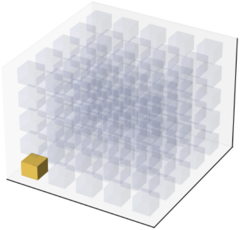
▶ which results could be more useful to get first ?

On traversal - Standard



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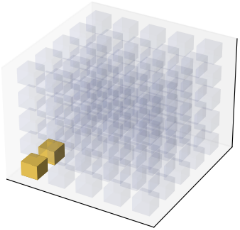

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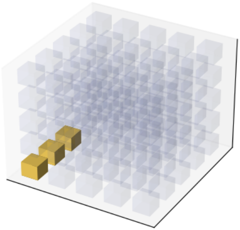

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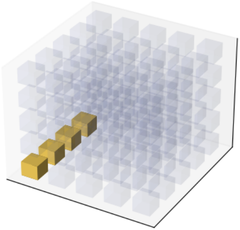

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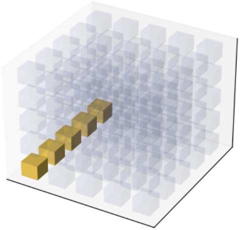

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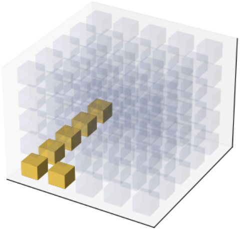

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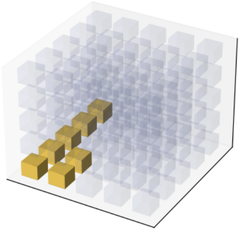

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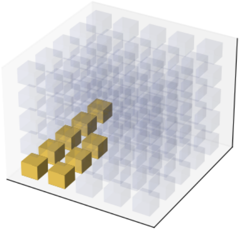

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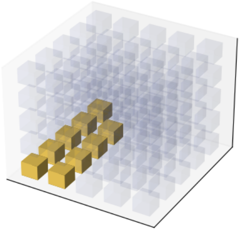

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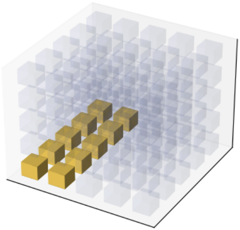
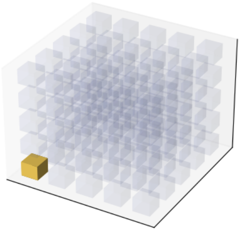


On traversal - Simple variation



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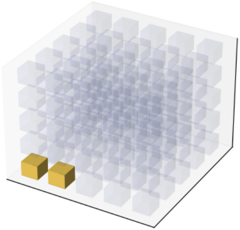

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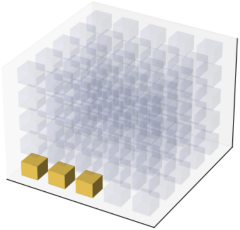

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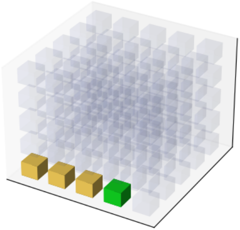

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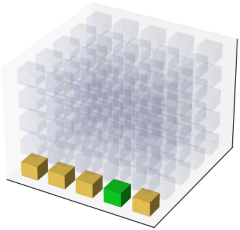
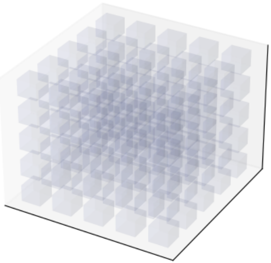


Good news : low expectations

On traversal - Educated guesses ?



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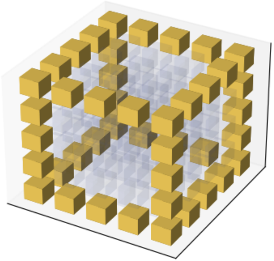

Out of normal range - Check if false positives

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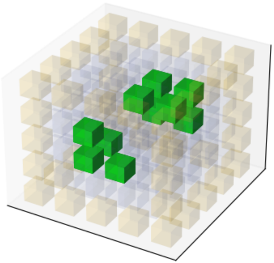

Out of normal range - Check if false positives

Two probable ecological niches

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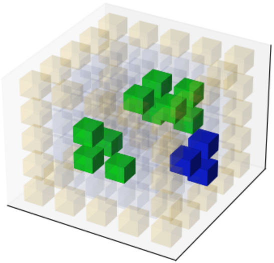

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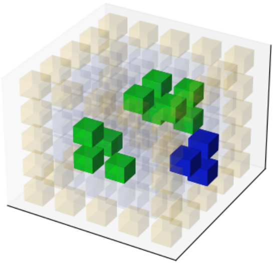

Out of normal range - Check if false positives

Two probable ecological niches

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Allow prioritization without loss or redundancy. Cost vs Precision

Getting the size right

Computing cost/time vs

cell sizes : vs parameter sensitivity
number of simulations : precision computing the property and additionnal statistics

Space : disk/network usage vs

storing information about visited cells : % match, avg distance, data reached, std. dev., best results found

A few strategies

- Stopping simulations before the end (depends on traces length/cache misses)
- **not running all simulations if the result won't probably reach expectations**
- filter or aggregate results to save space
- **getting partial results to test hypotheses on more effective discretisation**
- exploiting more info about intra-cell variability (quasi random instead of the costly Sobolov indices)

Shortcuts - Max SPRT

Max SPRT basically answers questions like

If the first 10 simulation failed and we want 90% match for good cells, how much is it worth continuing considering the precision we aim for ?

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But we want some info even on sub optimal regions, especially if the variability is high

- We configured Max SPRT to be a little more tolerant than our match threshold
- We keep additionnal info for the best simulation for each "interesting enough "cell

Pretending to zoom in - a hint

- We have a derived property comparing results from different simulations.
- We also kept the position and rewards for the best simulation found in each "interesting enough" cell.

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We can use this to partially answer the question "would we have found smaller common cells if we used a finer grained discretization ?"
Which is another way to select a subset of cells where it could be intersting to zoom in first.

Pretending to zoom in - how

- compute distances between best parameters of each cells
- use them to determine the "virtual size" of a cell which would have contained them all.
- sort them
- select the "smallest" virtual cells

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we know we're missing out a lot but looking for these small cells is a matter of seconds, not hours or days.

Pretending to zoom in - limitations

- Larger cells make room for best individual fits
  $\rightsquigarrow$ getting worse and worse solutions when reducing the "virtual" size of the cell
- filtering out too much alters the distribution
  $\rightsquigarrow$ the selection cease to be representative of good solutions

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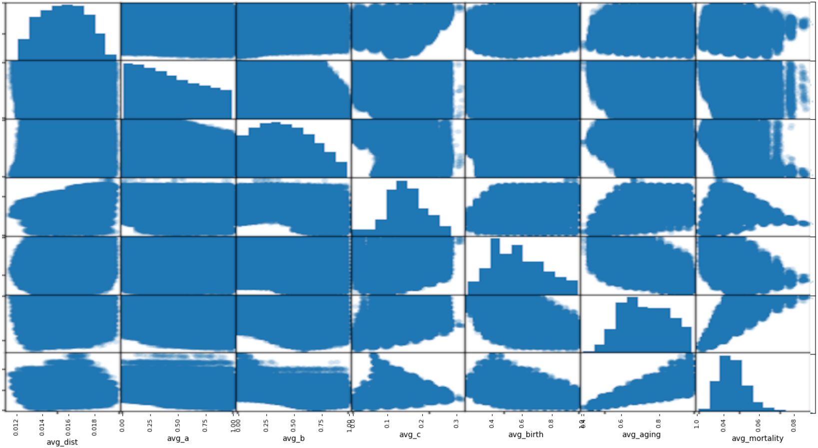
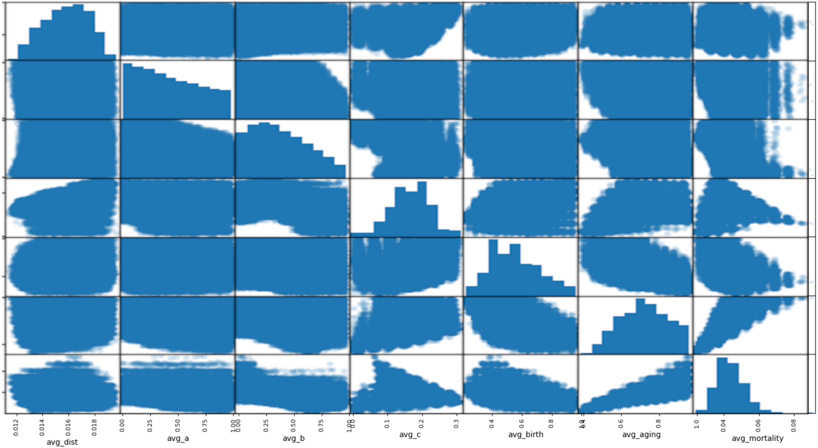
To know where to stop we must consider

- simulation scores (don't get too bad)
- global parameter distribution for "good" cells

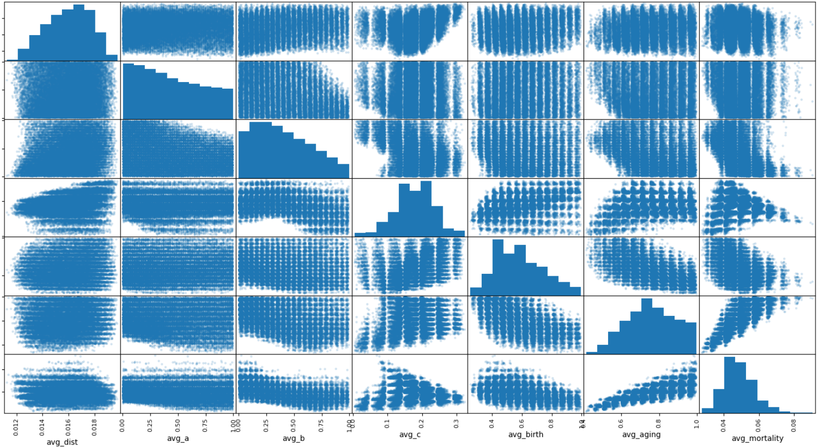
The original distribution



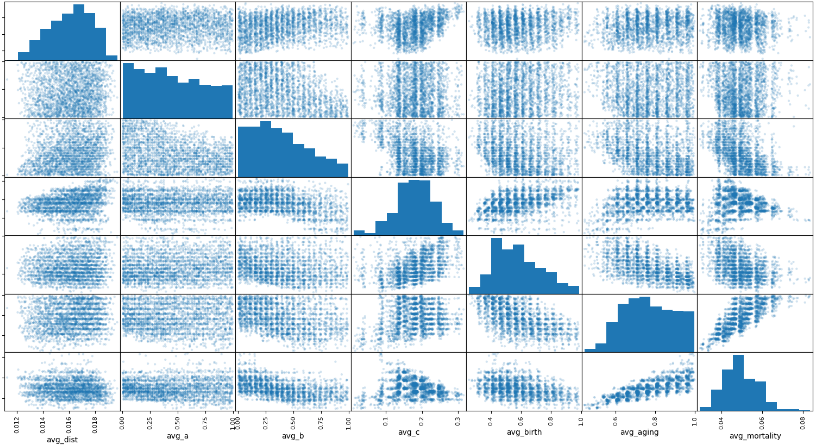
First quartile



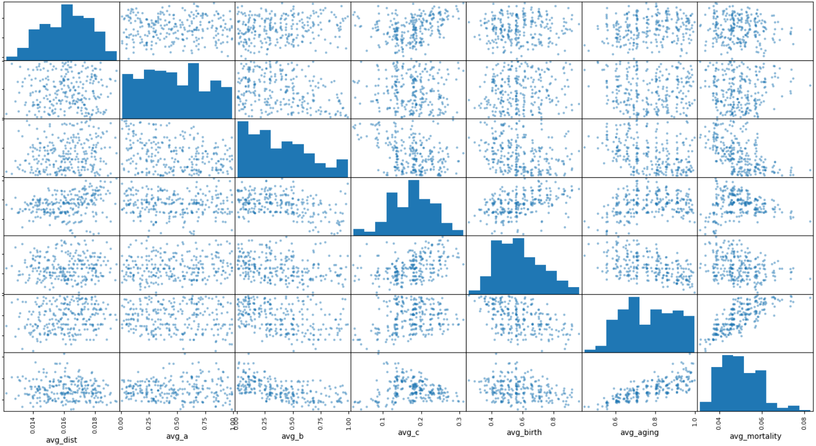
First decile



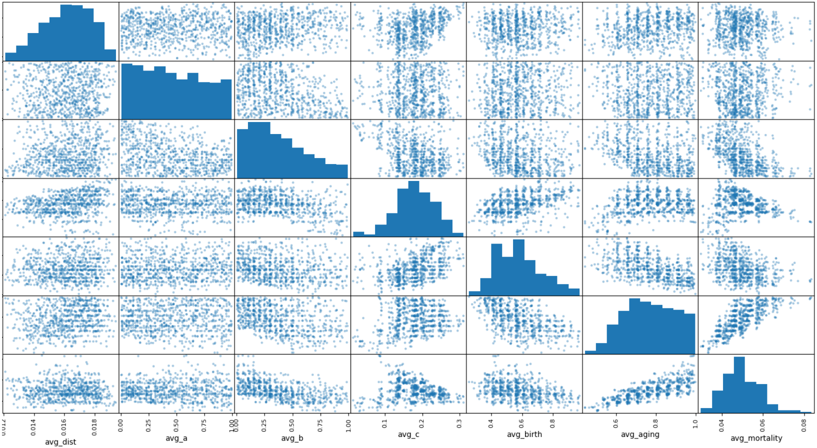
First centile



First millile



First 3 milliles



virtual zoom

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Keep in mind that differents splits strategies change the precision (the size of the subcells becomes heterogeneous)

Conclusion

An interesting use case

Plenty of future work

- the quest for good models is neverending
- optimization and trade offs (vs guaranties)
- useful and low cost metrics
- exploration strategies
- data mining, clustering

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I guess some might be seen as peripheral to the topic, but I believe that automating boring computations and put the user in charge of more meaningful decisions is a worthy goal.