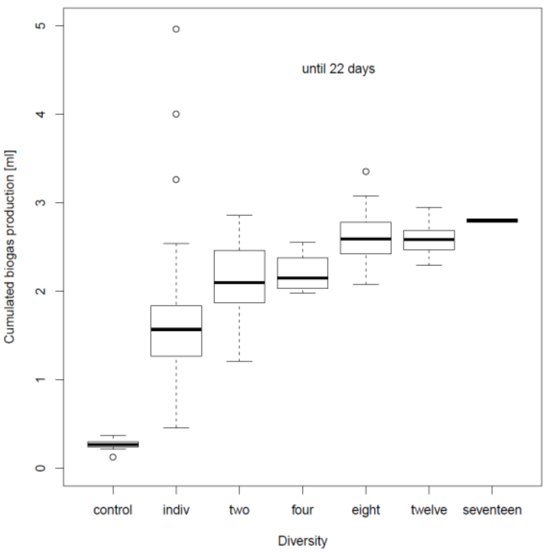
Overyielding in microbial ecosystems: what can we learn from modeling?

Jérôme Harmand



Overyielding in Microbial Ecosystems : What can we Learn from Modeling?

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CONTEXT

❖ Maximize bioprocess performances (for instance in terms of production rates or yields)

❖ Understanding conditions under which « overyielding » occurs

❖ Acting on the process instead of « suffering / undergoing » their properties…

❖ How model can help?

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Overyielding: a question of interactions?

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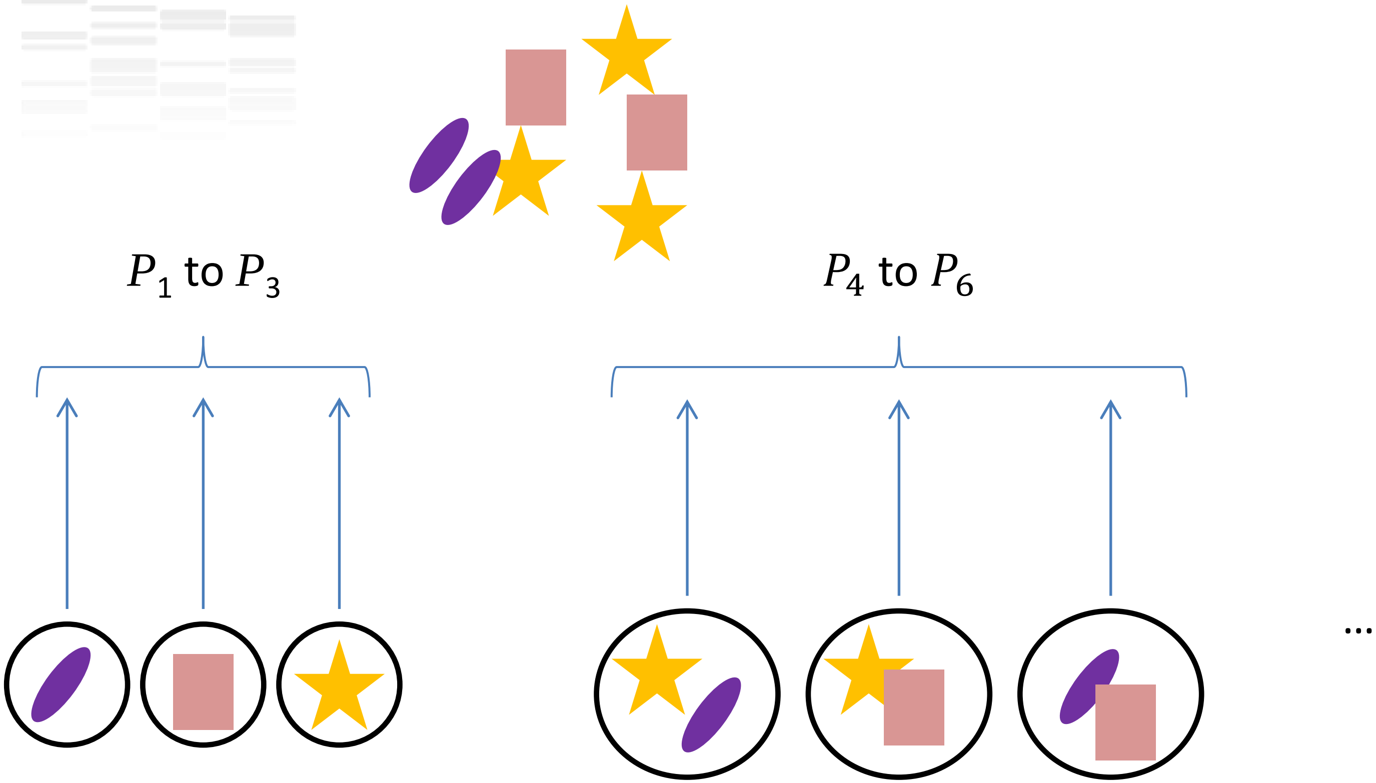
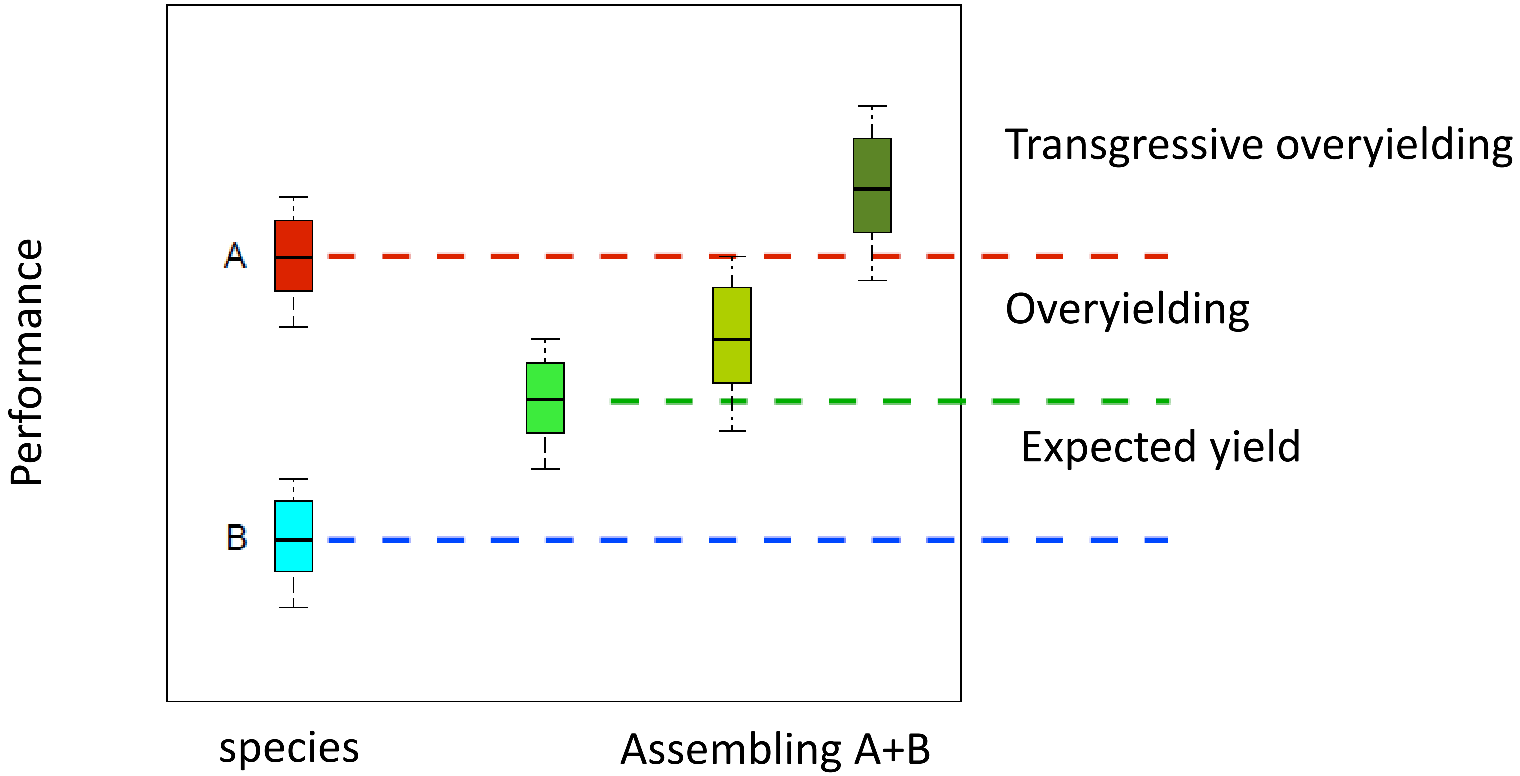
Overyielding

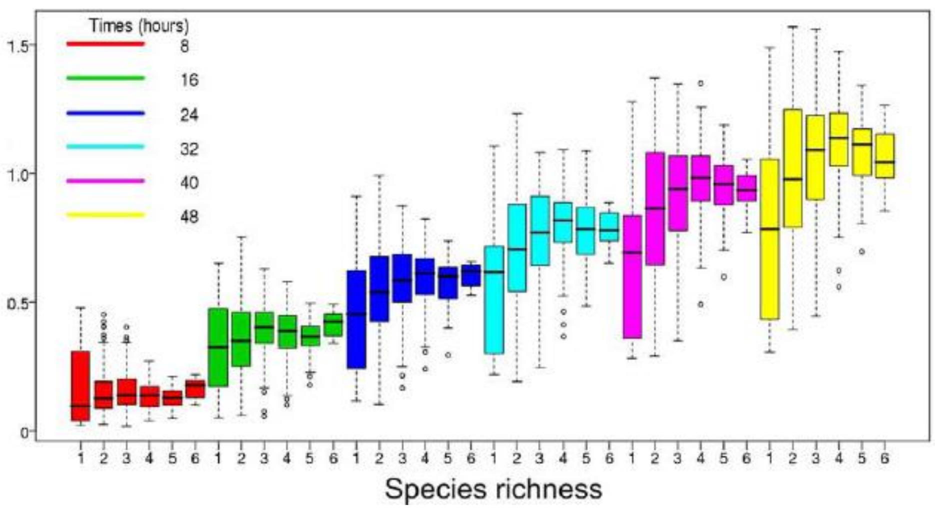


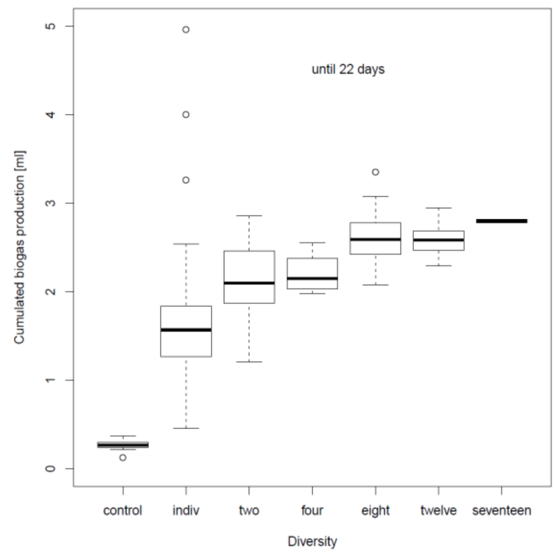
If there exists $P_i|_{i=4..6} > \max(P_i|_{i=4..6})$, then there is overyielding and it is said to be transgressive

Overyielding



Overyielding





Modeling : competition for a limiting substrate

Consider :

$$\begin{cases} \dot{X}_i &= \mu_i(S)X_i \\ \dot{S} &= -\sum_{i=1}^{n} \frac{\mu_i(S)}{Y_i} X_i \end{cases}$$

Then : $\sum_i \frac{\dot{X}_i}{Y_i} + \dot{S} = 0 \Longrightarrow \sum_i \frac{X_i(T) - X_i(0)}{Y_i} = S(0) - S(T)$

If $S(T)$ is negligible compared to $S(0)$ (hypothesis H1), then :

$$\sum_i \frac{(X_i(T) - X_i(0))}{Y_i} \simeq S(0)$$

If $p_i = \frac{X_i(T) - X_i(0)}{Y_i S(0)}$ then $\sum_i p_i = 1$

Modeling : competition for a limiting substrate

Under H1, the biogas produced from 0 to T is :

$$
\begin{aligned}
SQ_{gaz}(T) &= \int_0^T \sum_i k_i \mu_i \left(S(\tau)\right) X_i(\tau) d\tau \\
&= \int_0^T \sum_i k_i \dot{X}_i(\tau) d\tau \\
&= \sum_i k_i \left(X_i(T) - X_i(0)\right) \\
&= S(0) \sum_i k_i Y_i p_i
\end{aligned}
$$

Modeling : competition for a limiting substrate

Under H1, we have :

$$SQ_{gaz}(T) = S(0)\sum_i k_i Y_i p_i \leq S(0)\sum_i \max_i(k_i Y_i) p_i = S(0) k_{i*} Y_{i*} \sum_i p_i = S(0) k_{i*} Y_{i*}$$

where *i** is such that $k_{i^\star} Y_{i^\star} = \max_i k_i Y_i$.

1. H1 => max(biogaz(T)) obtained in pure culture;

2. The simple competition model cannot explain overyielding but MORE IMPORTANTLY,…

Modeling : competition for a limiting substrate

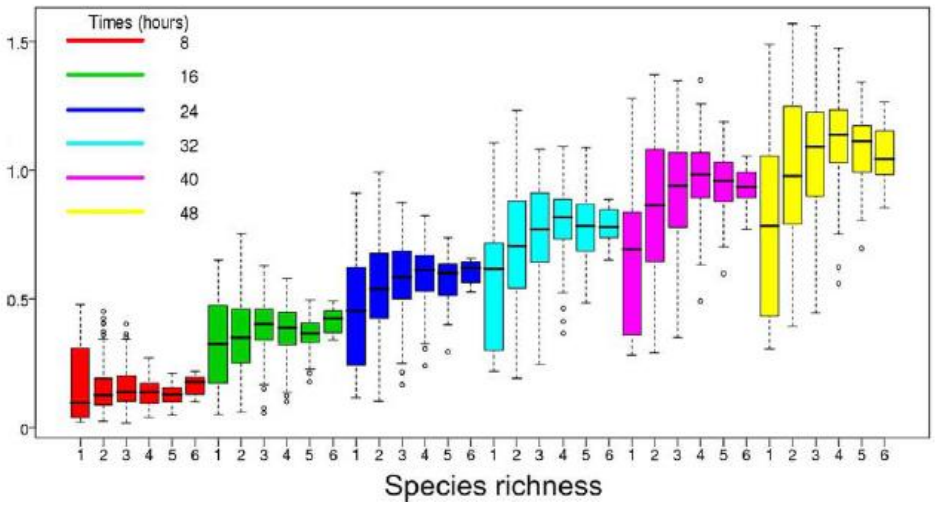
…RESULTS DO NOT DEPEND ON $\mu_i(.)$!

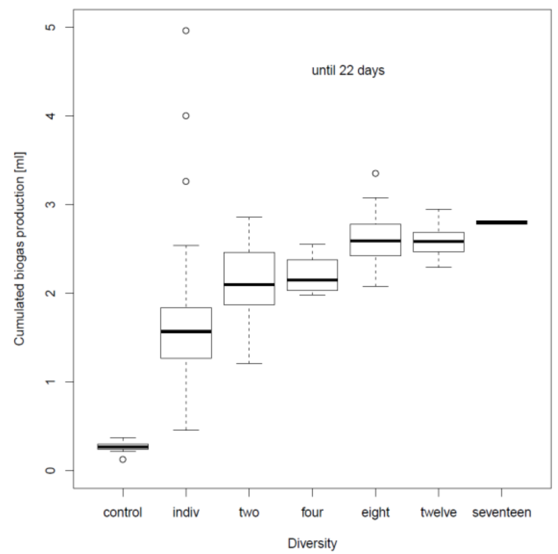
Indeed they remain true for the system :

$$\begin{cases} \dot{X}_i = \mu_i(.)X_i \\ \dot{S} = -\sum_{i=1}^{n} \frac{\mu_i(.)}{Y_i} X_i \end{cases}$$

3. Results remain valid for any biotic interactions modeled into kinetics functions (density-dependence, Generalized Lotka-Volterra…)! *In fact, for any process engineer it is obvious! If the yield is constant, the quantity of biogaz to be produced over a period of time does only depend on the quantity of resource and not on the kinetics at which it is produced!*

Overyielding : non modeled phenomena?





Other interactions than those modeled into kinetics!
Which phenomena could be in play?

_02 Searching for non modeled phenomena

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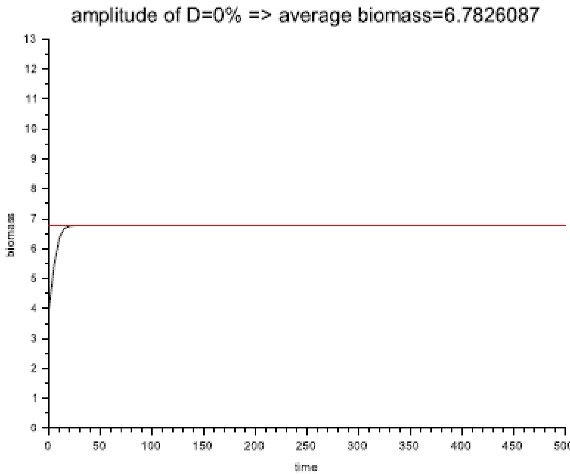
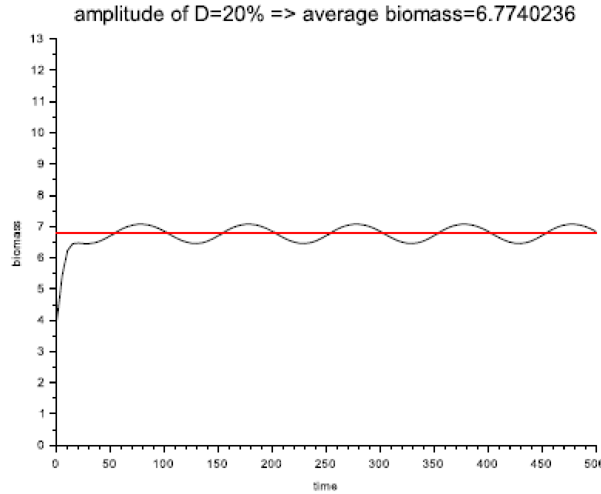
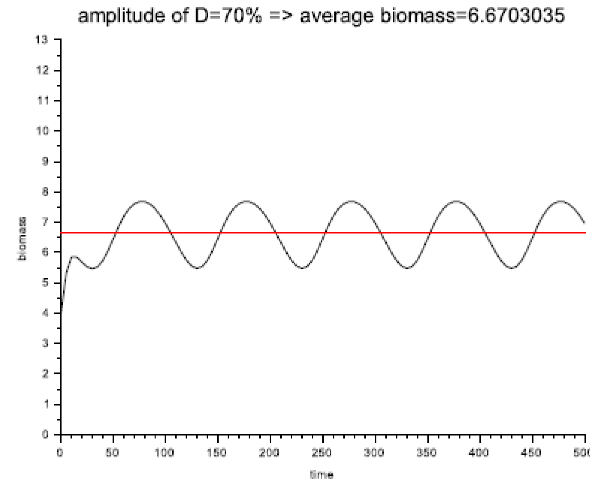
How overyielding occurs in continuous processes?

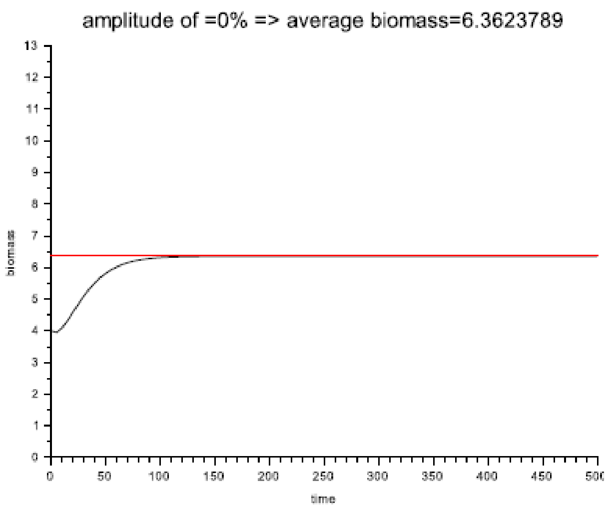
In continuous processes, density-dependence (actually ratio-dependence) + varying inputs may lead to the appearance of overyielding!

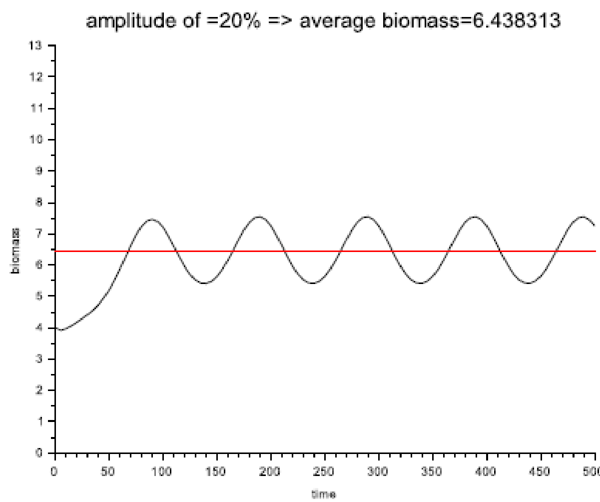
Simulation results

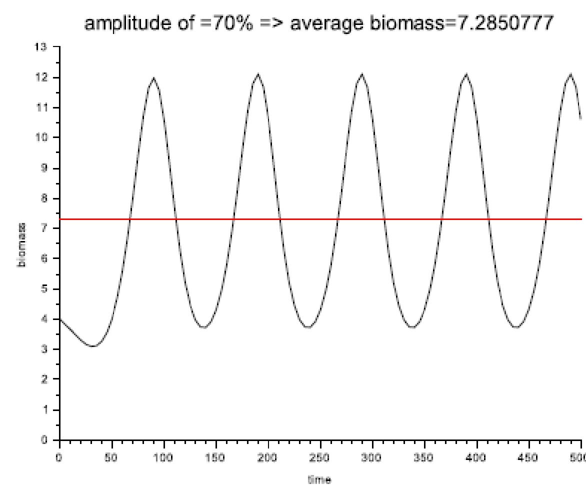












Hypotheses : role of other phenomena?

- Variable yields
- Recycling matter (mortality)
- Maintenance
- Higher the diversity, higher the probability of having microorganisms able to pre-treat a number of non biodegradable molecules (that are then avaialable for others)…
- Higher the diversity, higher the probability of having predators (for example viruses) that make a part of the biomass available as substrates…
- …

A question…

What may significantly differ a batch from a continuous process ?

➔ Mortality ? 🡐

Indeed, because of the presence of a dilution rate, the mortality can sometimes be neglected in continuous processes while it cannot in batch processes…

A new model for batch process

Including mortality in the batch model

$$\begin{cases} \dot{X}_i = (\mu_i(.) - d)X_i \\ \dot{S} = -\sum_{i=1}^{n} \frac{\mu_i(.)}{Y_i} X_i \end{cases}$$

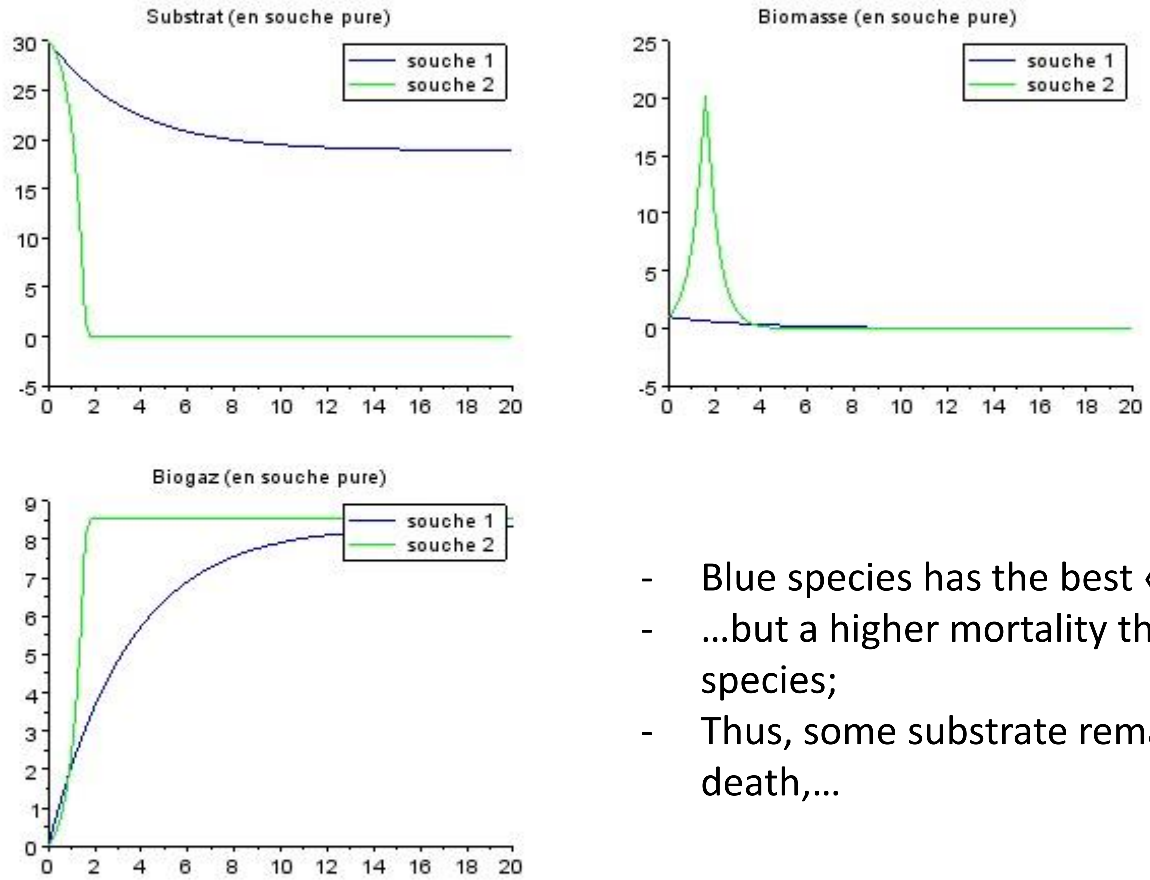
Overyielding can now occur!

Explanation

In the presence of mortality, the biomass concentration will decay and tends towards zero. In such a case, it can be shown that there necessarily will remain some substrate for arbitrarily large T. Thus, in the presence of several species, the remaining substrate can be used by a species having a lower decay rate than those who have « disappeared already », improving then the total biogas production…

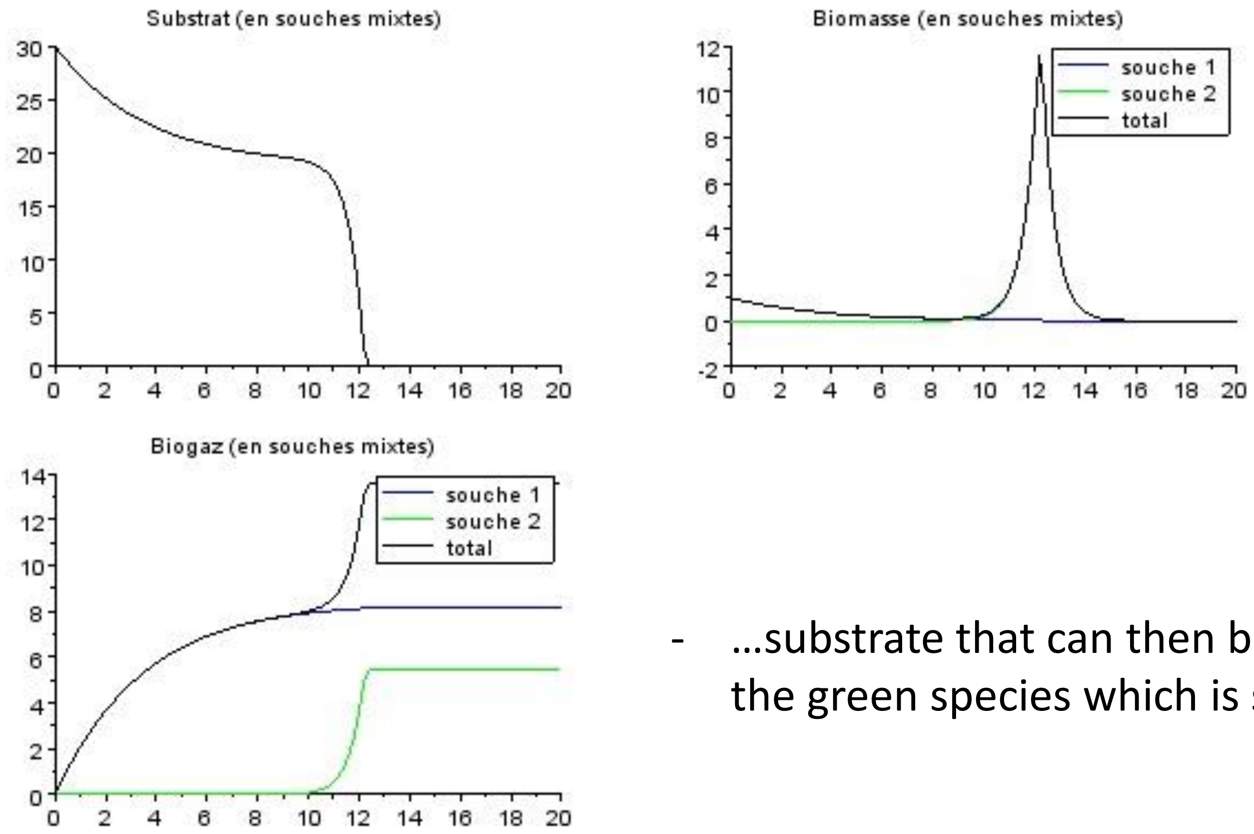
Hypotheses

Simulations



- Blue species has the best « Y.r »…
- …but a higher mortality than the green species;
- Thus, some substrate remains after its death,…

Explanations



- …substrate that can then be used by the green species which is still alive!

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Conclusions and perspectives

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Conclusions and perspectives

- Over yielding in batch cannot be explained by classical models of N species in competition on a limiting substrate;
- If mortality is included, overyielding may appear;
- *« Engine of overyielding » are of different nature in batch and in continuous bioreactors…*
- We must now inventory i) possible (candidates) phenomena to be studied to allow overyielding and ii) identify possible experiments to sort out the most probable phenomena in play in real ecosystems.

Thank you for your attention!