Long-term dynamics of a simplified DEB-based ecosystem model

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Paper

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A simple DEB-based ecosystem model

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Figure 1: Embroidering on earlier work by Bas Kooijman and Roger Nisbet, this paper describes in detail a canonical community model based on DEB theory.

Content

- Context: The future of global marine food systems
- The canonical ecosystem model
- The simplified model
- Approach: bifurcation analysis
- Results and conclusions

The future of global marine food systems

- How much food can the oceans and seas provide, after a fisheries-aquaculture transition?
- An ecosystem-based view with an emphasis on energy fluxes and nutrient and mass balances in marine systems
- Use DEB theory

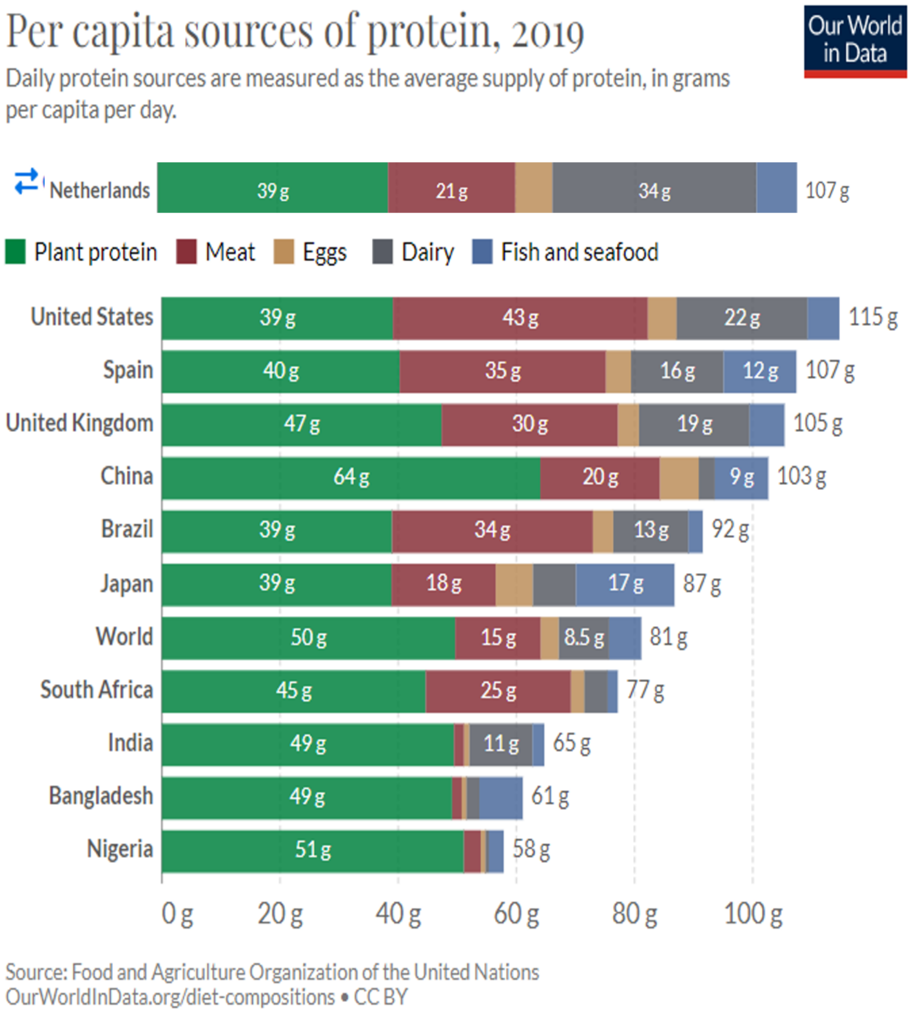

Figure 2: Protein intake.

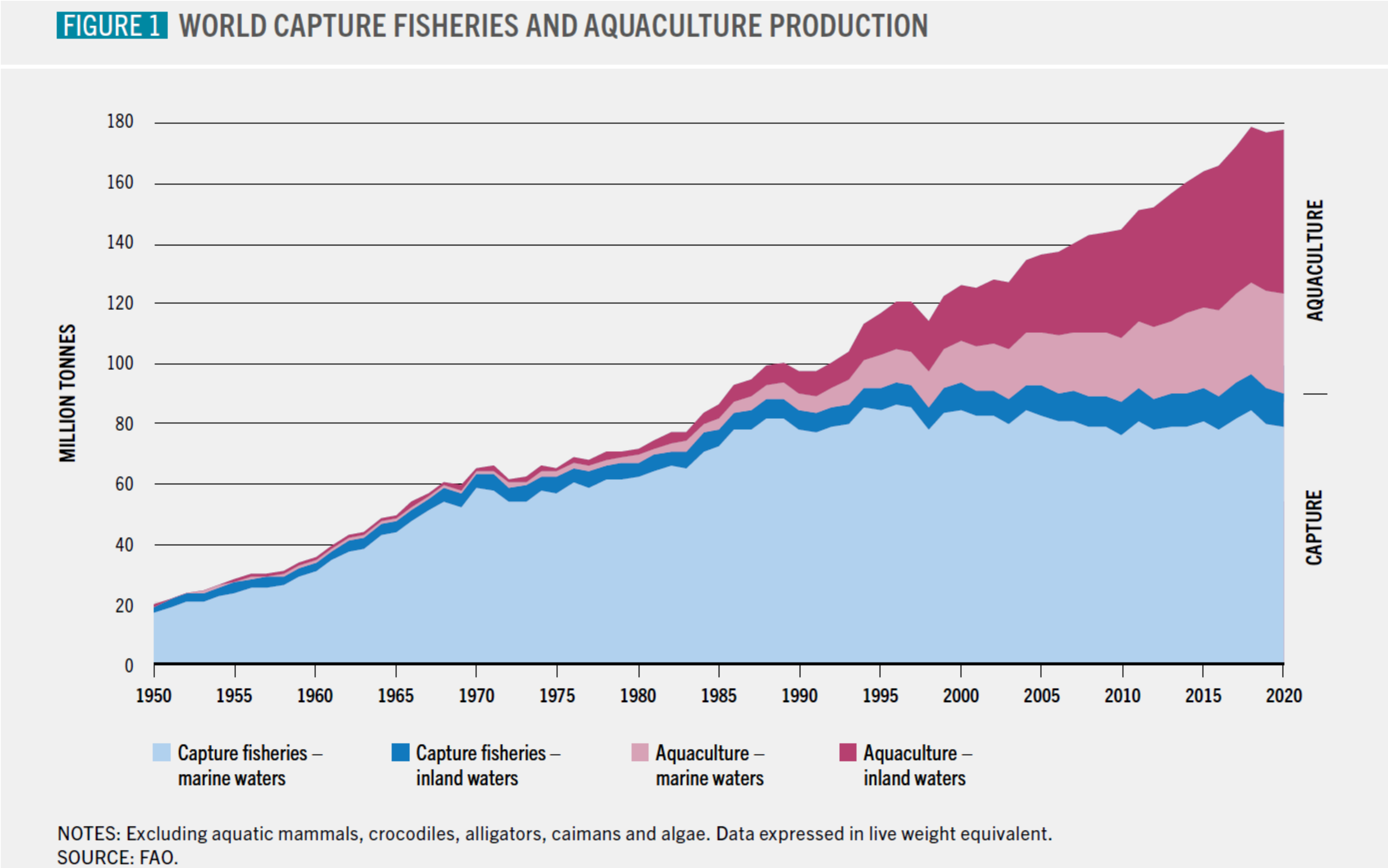

Figure 3: Fishery and aquaculture yields.

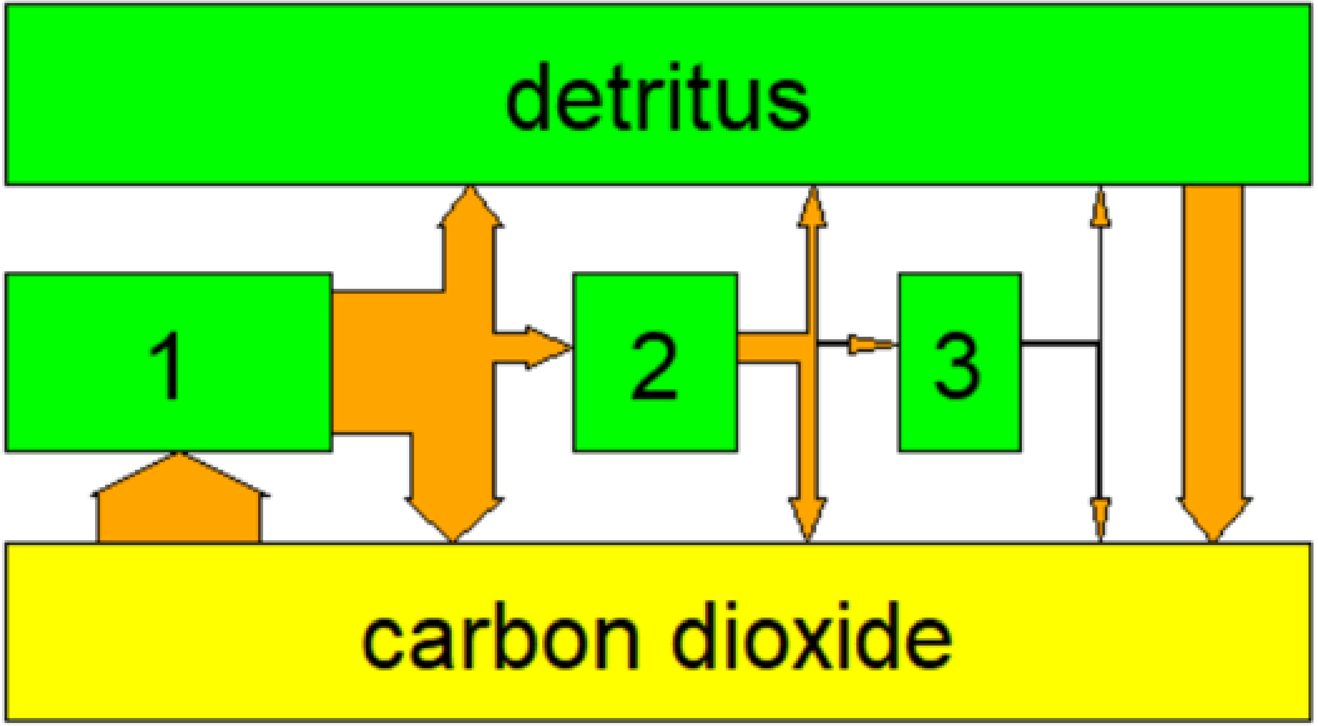

Figure 4: The cycle of life: PP, efficiency and trophic level.

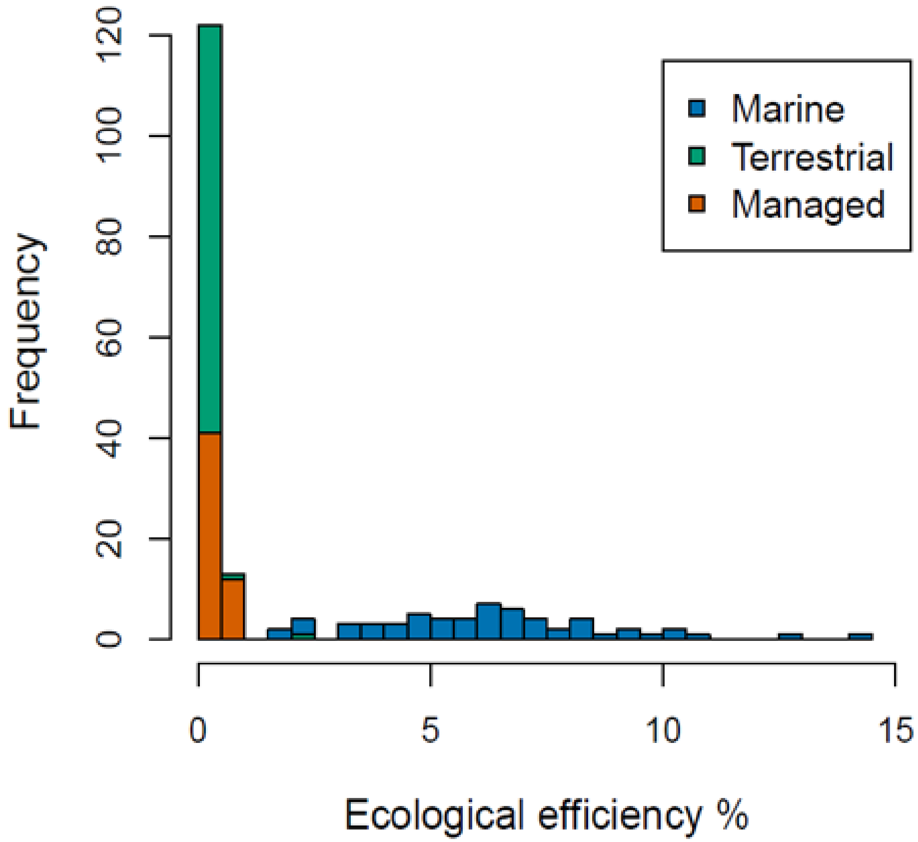

Figure 5: Trophic efficiency.

Lessons from farming and ecology

- Finfish aquaculture at sea is not a very promising avenue to increase 'true' marine food production

- Replace hardly harvestable phytoplankton and zooplankton by seaweed and shellfish

- Take account of possible nutrient depletion and decreasing primary production

Canonical ecosystem model

The canonical ecosystem model is a DEB-based model for V1-morphs, formulated in a mass-mass framework and keeping track of carbon and nitrogen fluxes.

It contains apart from the nutrients carbon dioxide and ammonia, three living (producers, consumers and decomposers) and one non-living group (detritus). Each living group is characterized by a structure and by two (producers) or one (the other two groups) type of reserves. Detritus is split up in 4 types, depending on the origin, which can either be consumer faeces as a result of eating producers, consumer faeces from eating decomposers, consumer dead structure or consumer dead reserves.

The model has therefore 13 state variables. As the system is closed for matter, the dynamics of the nutrients follow automatically from the dynamics of the other 11 state variables.

Table 1: State variables of the canonical ecosystem model. The first letter of the index stands for the type of compound. The second letter stands either for the origin of the faeces or for the group.

Group	Compound	Variable
Detritus	Producer faeces	M_{PP}
Detritus	Decomposer faeces	M_{PD}
Detritus	Dead consumer structure	M_{PV}
Detritus	Dead consumer reserve	M_{PE}
Consumer	Structure	M_{VC}
Consumer	Reserve	M_{EC}
Producer	Structure	M_{VP}
Producer	Reserve 1	M_{E_1P}
Producer	Reserve 2	M_{E_2P}
Decomposer	Structure	M_{VD}
Decomposer	Reserve	M_{ED}
Nutrient	Carbon dioxide	M_C
Nutrient	Ammonia	M_N

Table 2: The flux matrix. Columns refer to state variables, rows to the various processes: A assimilation, G growth, D dissipation, H death, and (second letter) C consumer, P producer and D decomposer.

	PP	PD	PV	PE	VC	EC	VP	E_1P	E_2P	VD	ED
A_1C	+					+	-	-	-		
A_2C		+				+				-	-
GC					+	-					
DC					-	-					
HC			+	+	-	-					
A_1P								+			
A_2P									+		
GP							+	-	-		
DP							-	-	-		
A_1D	-										+
A_2D		-									+
A_3D			-								+
A_4D				-							+
GD										+	-
DD										-	-

Model dynamics

- Stable periodic attractor with a one-year period
- Spring and autumn bloom
- Producers start, followed by consumers, detritus and decomposers
- Large fluctuations despite low nitrogen concentration
- Near-zero values may cause numerical problems

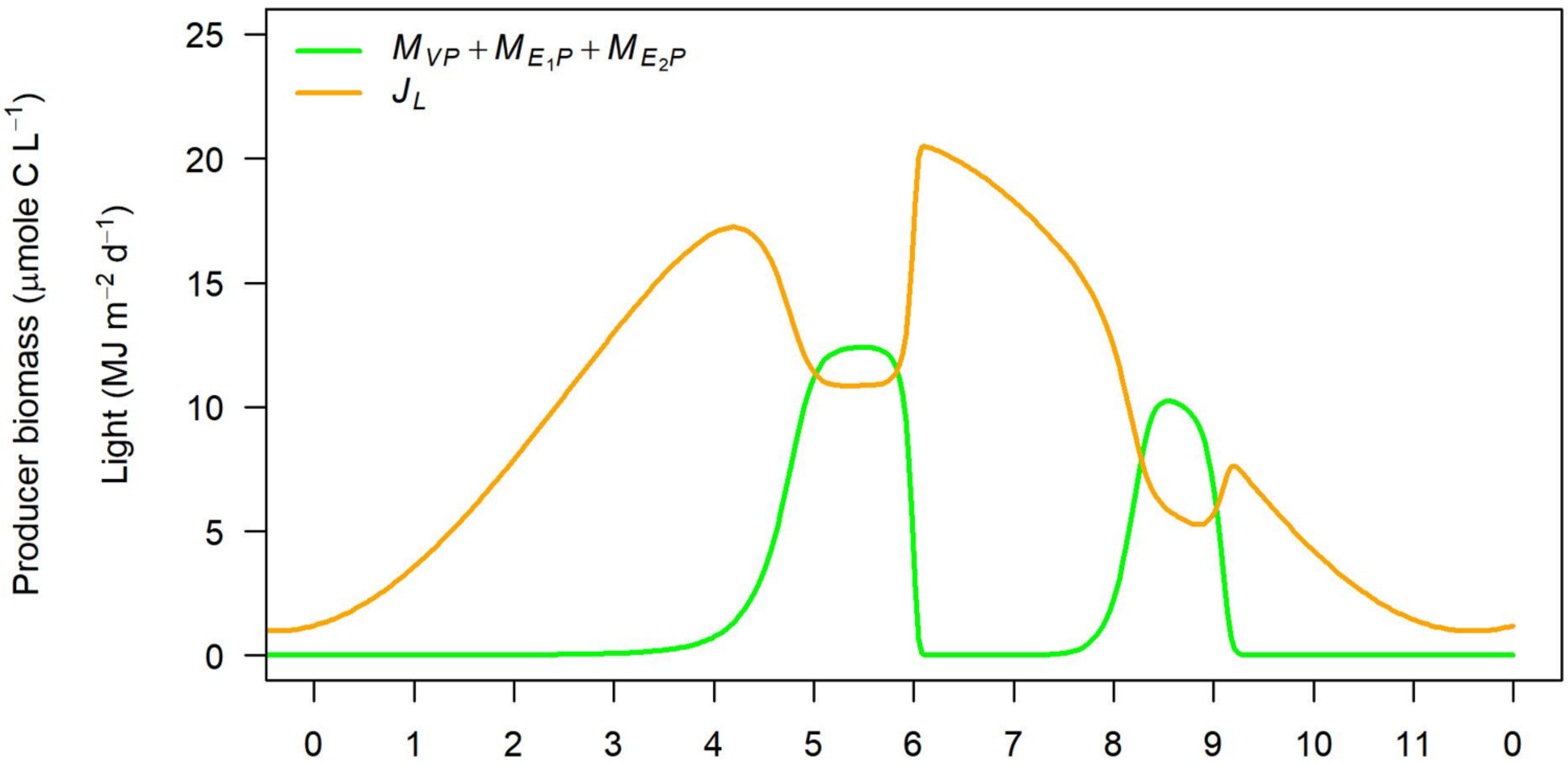

Figure 6: Dynamics of the canonical ecosystem model in the yearly repeating stable attractor. Plotted in the last year of a simulation over 5 years. Light and producer.

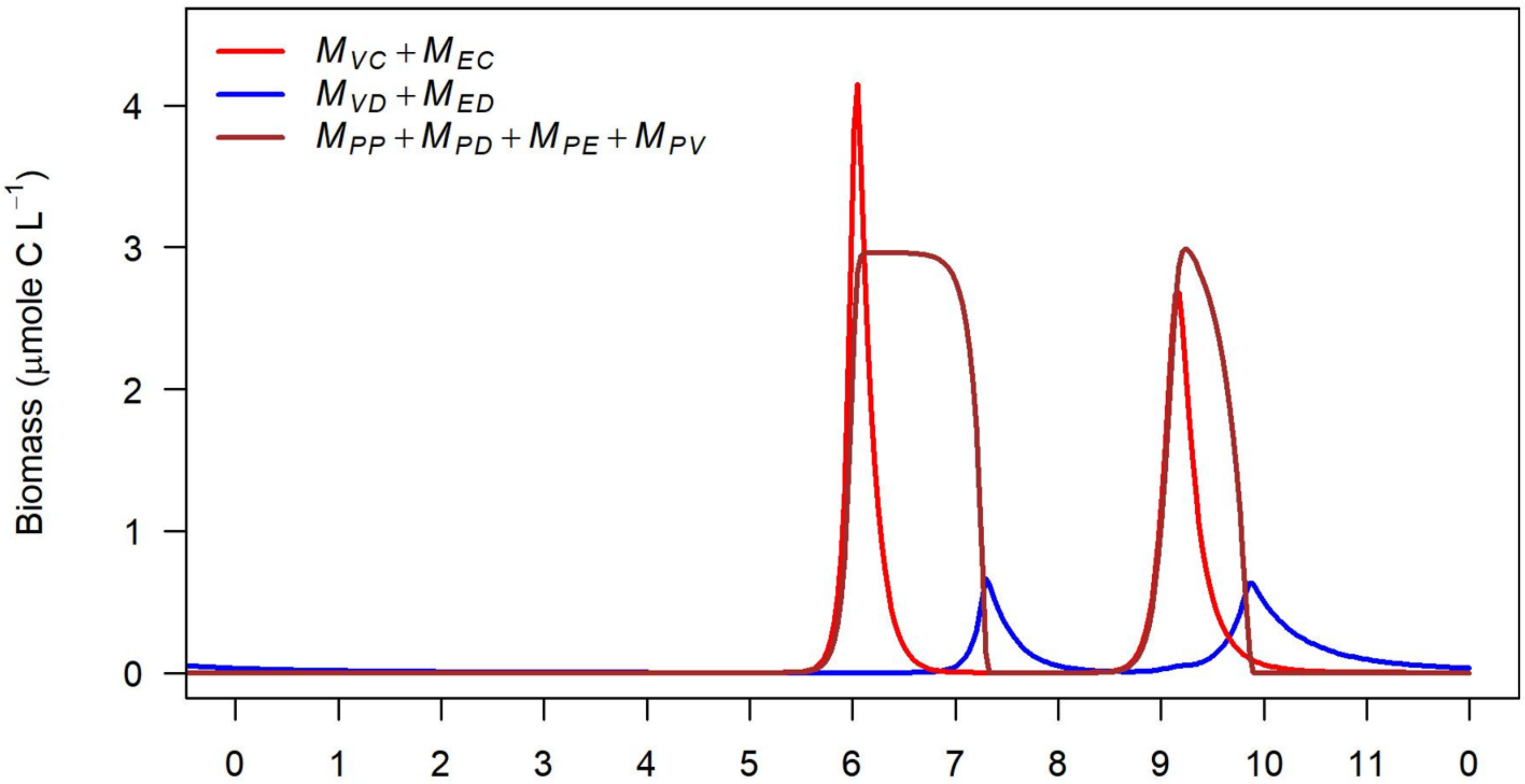

Figure 7: Dynamics of the canonical ecosystem model in the yearly repeating stable attractor. Plotted in the last year of a simulation over 5 years. Consumer, decomposer and detritus.

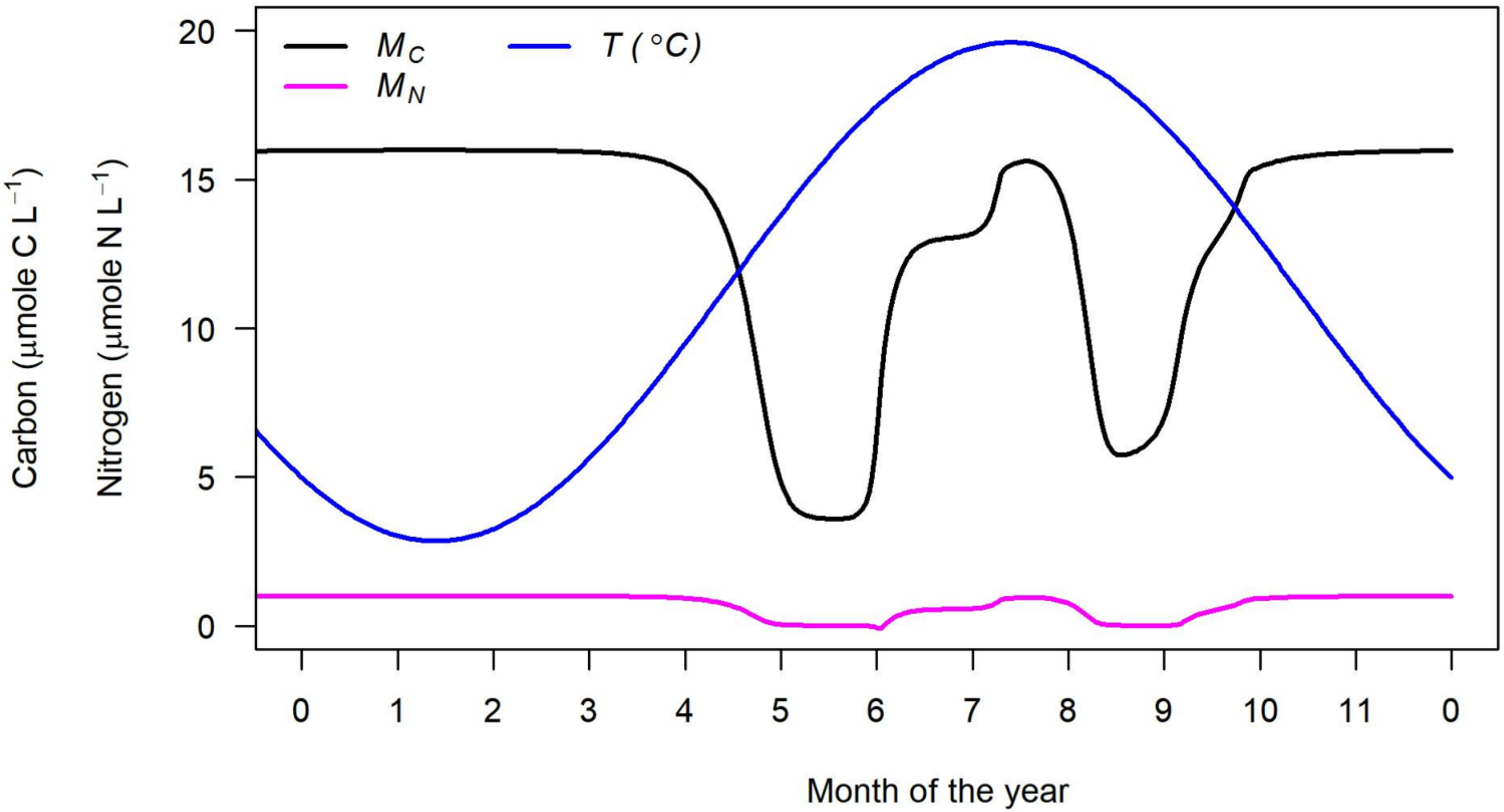

Figure 8: Dynamics of the canonical ecosystem model in the yearly repeating stable attractor. Plotted in the last year of a simulation over 5 years. Temperature and nutrients.

The simplified model

Table 3: The four state variables and the two nutrients of the simplified canonical ecosystem model. The first letter of the index stands for the type of compound, V structural mass, E reserves, C carbon-dioxide, and N ammonia. The second letter stands for the group, C consumer, and P producer.

Group	Compound	Variable
Consumer	Structure	M_{VC}
Consumer	Reserve	M_{EC}
Producer	Structure	M_{VP}
Producer	Reserve	M_{EP}
Nutrient	Carbon-dioxide	M_C
Nutrient	Ammonia	M_N

Table 4: The flux matrix $\dot{J}^T$. Columns refer to state variables, rows to the various processes, where (first letter) A stands for assimilation, G for growth, C for mobilization, H for death, and (second letter) C for consumer, and P for producer. A minus sign indicates a disappearing flux.

	VC	EC	VP	EP
AC		$+$	-	-
GC	$+$			
CC		-		
HC	-	-		
AP				$+$
GP			$+$	
CP				-

Approach: bifurcation analysis

- First, total nitrogen content and annual mean daily light irradiation were varied, while assuming no seasonality in irradiation or temperature

- Second, all other parameters were varied between a factor 0.8 and 1.25 around the original value

- Third, one example parameter that strongly affected the dynamics was varied while irradiation and temperature fluctuated seasonally, both at a low and at a high total nitrogen content

- For each chosen parameter set, model dynamics was simulated, point equilibria were numerically estimated, the eigenvalues of the Jacobian matrix evaluated in the equilibrium were calculated, and Poincaré plots were drawn.

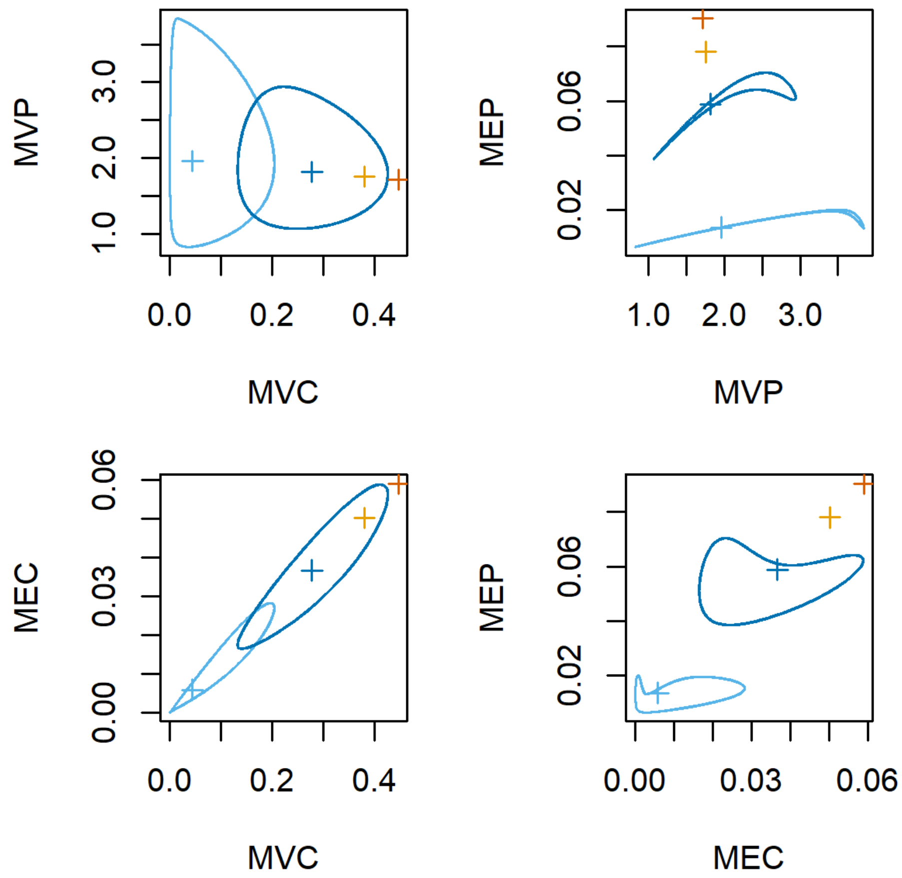

Figure 9: Projected phase plane diagrams at low total nitrogen content, and for four different irradiation levels. At low light conditions (blue) the equilibrium is unstable and stable limit cycles occur.

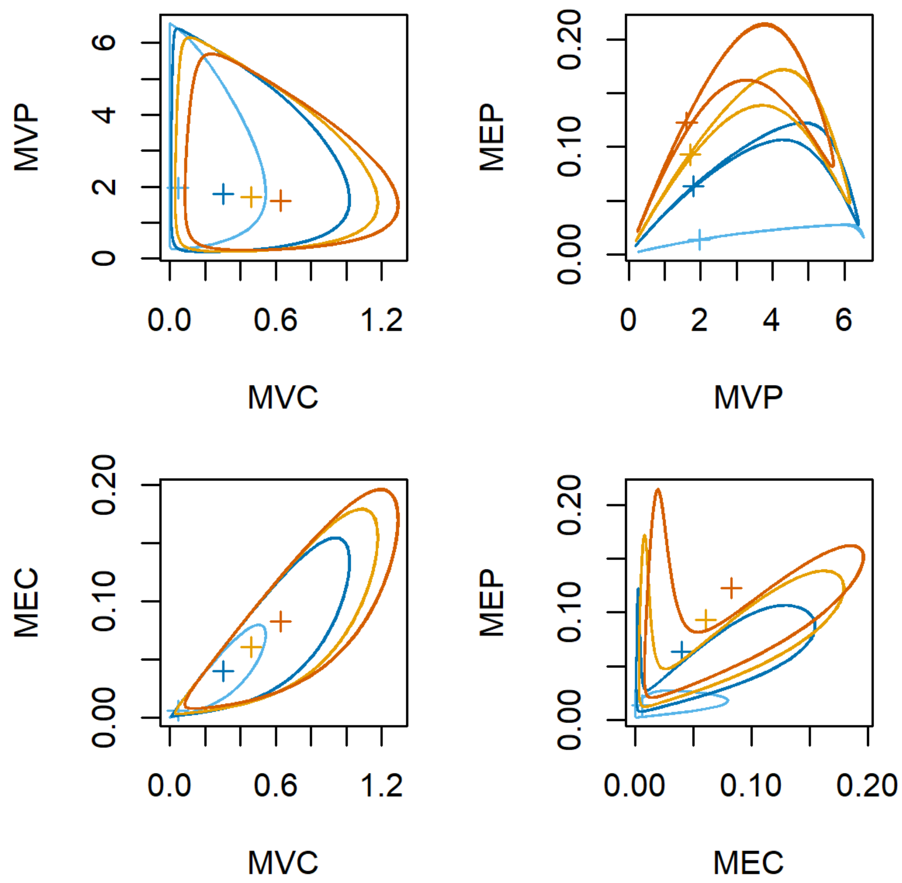

Figure 10: As Fig. 9, but at a high total nitrogen content. In all cases the equilibrium is unstable.

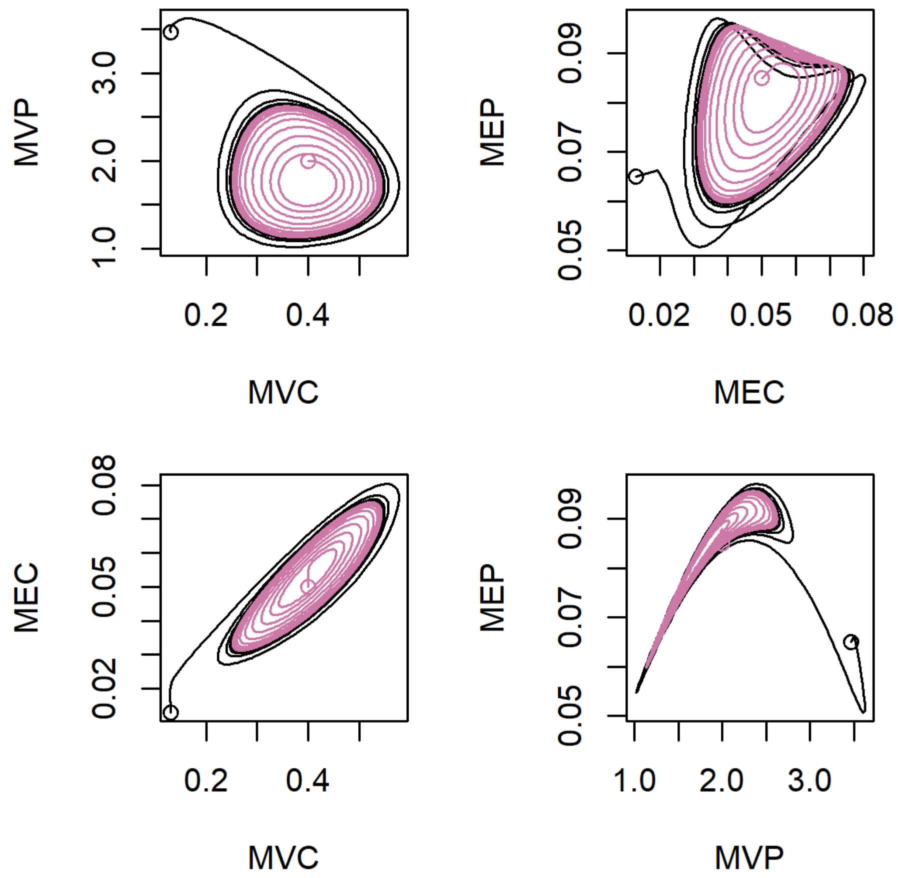

Figure 11: Example of a stable limit cycle, which is approached from two different sets of initial values. Dots show the initial values.

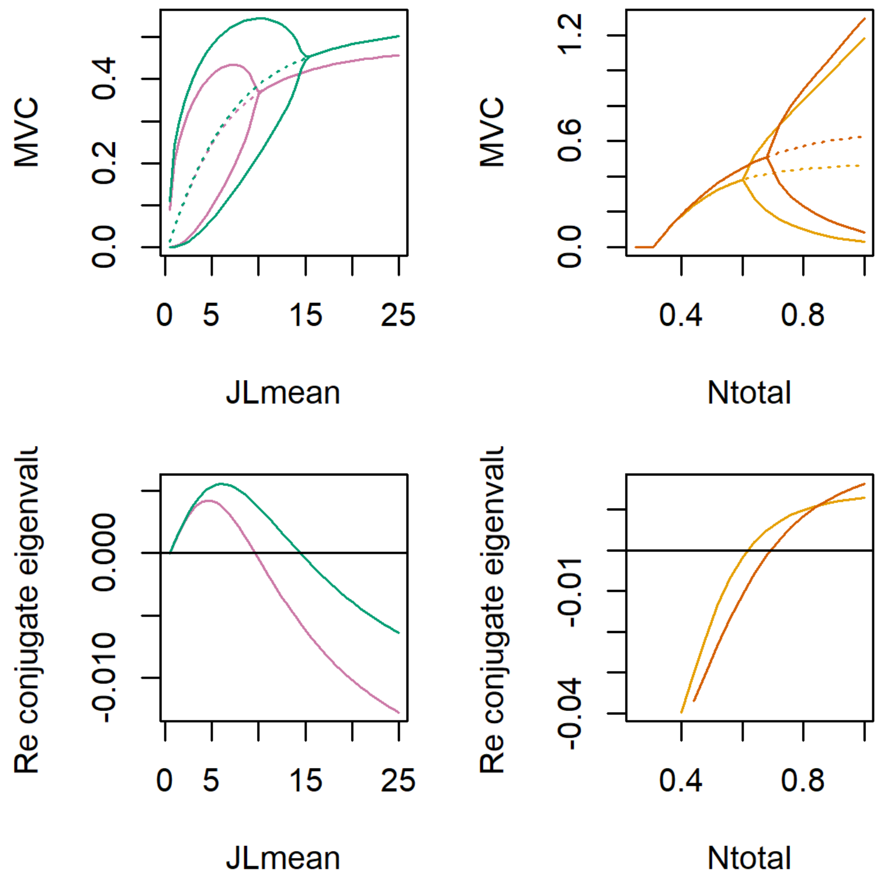

Figure 12: One-parameter bifurcation diagrams. For low irradiation levels (below the Hopf bifurcation point) the equilibria are unstable and the system oscillates with extrema indicated by solid lines. At irradiation levels above the bifurcation point the equilibria are stable. Lower panels show the real part of the conjugate eigenvalue pair.

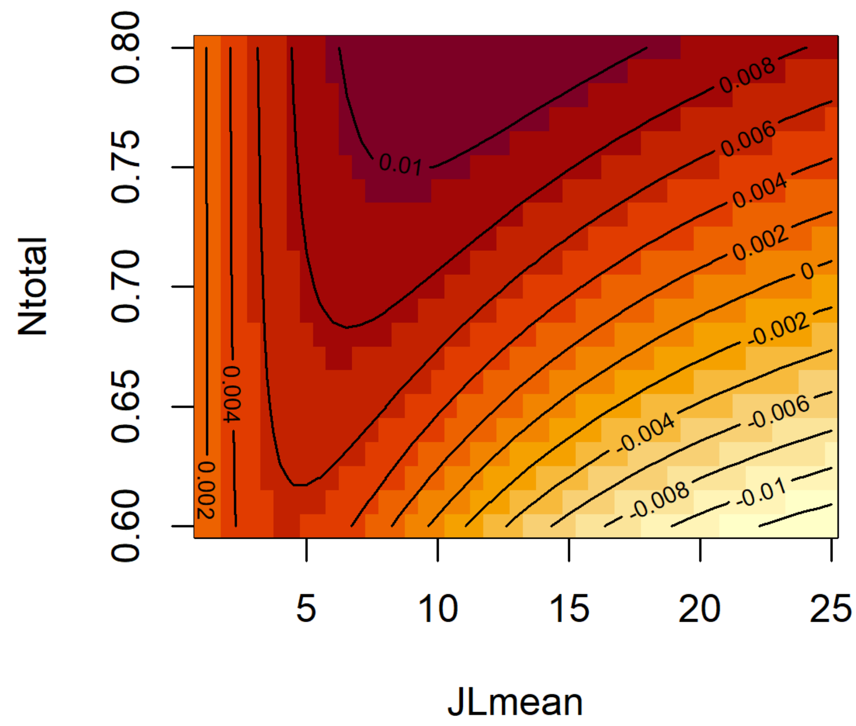

Figure 13: The real part of the conjugate eigenvalue pair as a function of light and nitrogen. A negative real part (lower right of the figure) points to a stable point equilibrium.

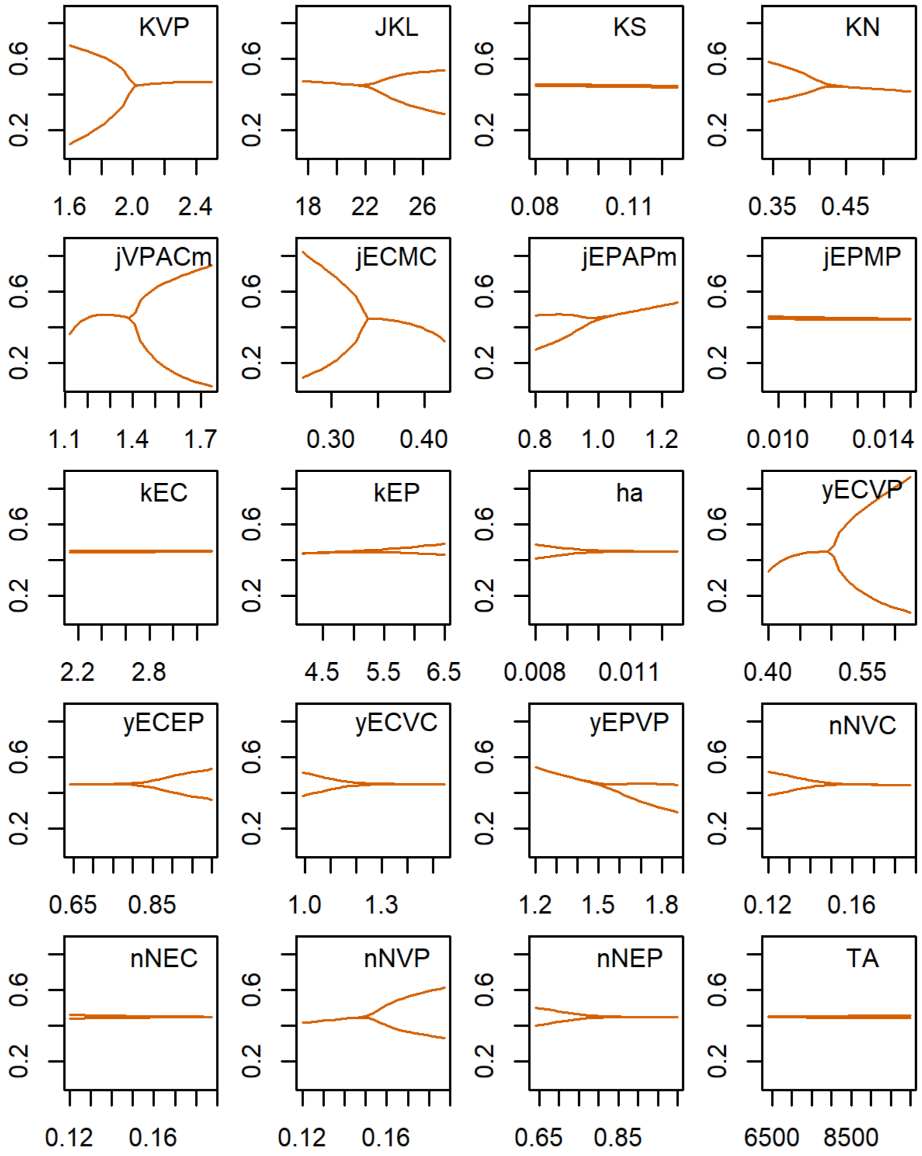

Figure 14: One-parameter bifurcation diagrams.

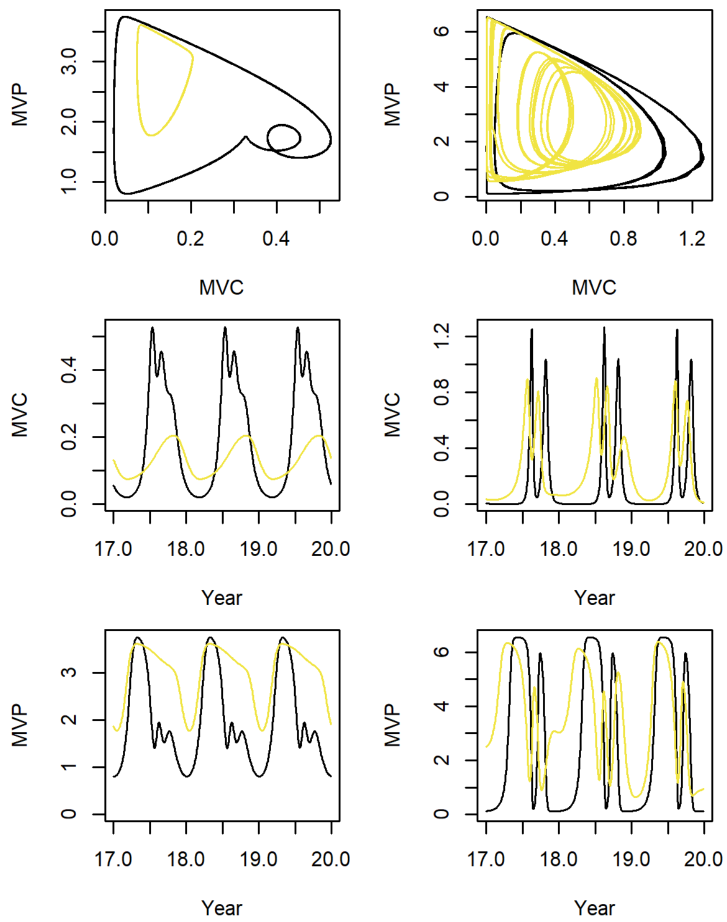

Figure 15: Total nitrogen content low (left) or high (right); yellow lines refers to a low (y_{ECVP}=0.4) and black lines to a high conversion efficiency from producer's structural mass to consumer's reserves (y_{ECVP}=0.5).

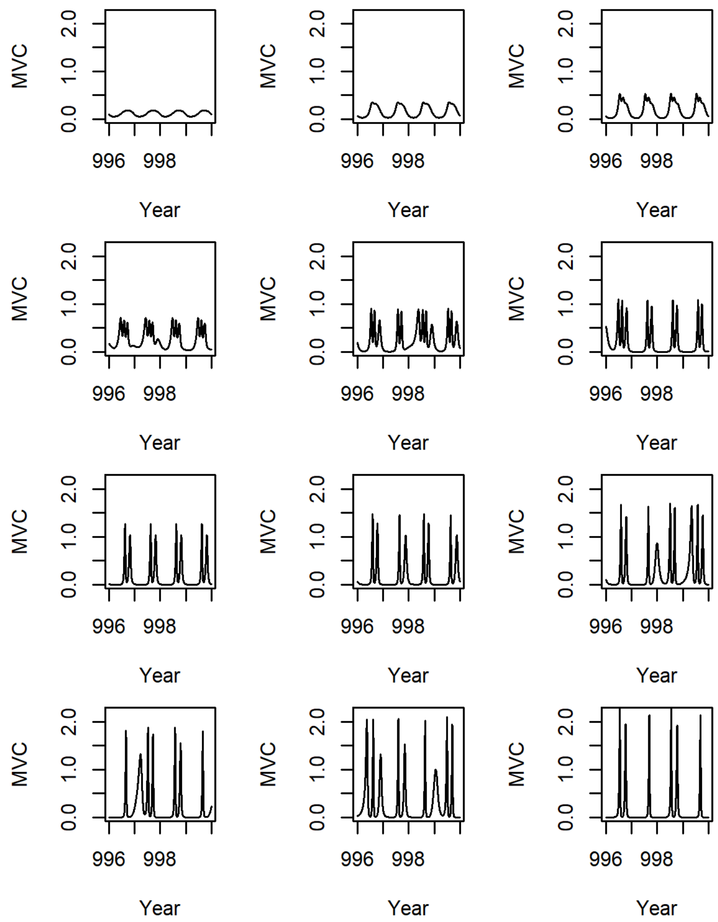

Figure 16: Time series plots. From upper to lower panels, increasing total nitrogen content.

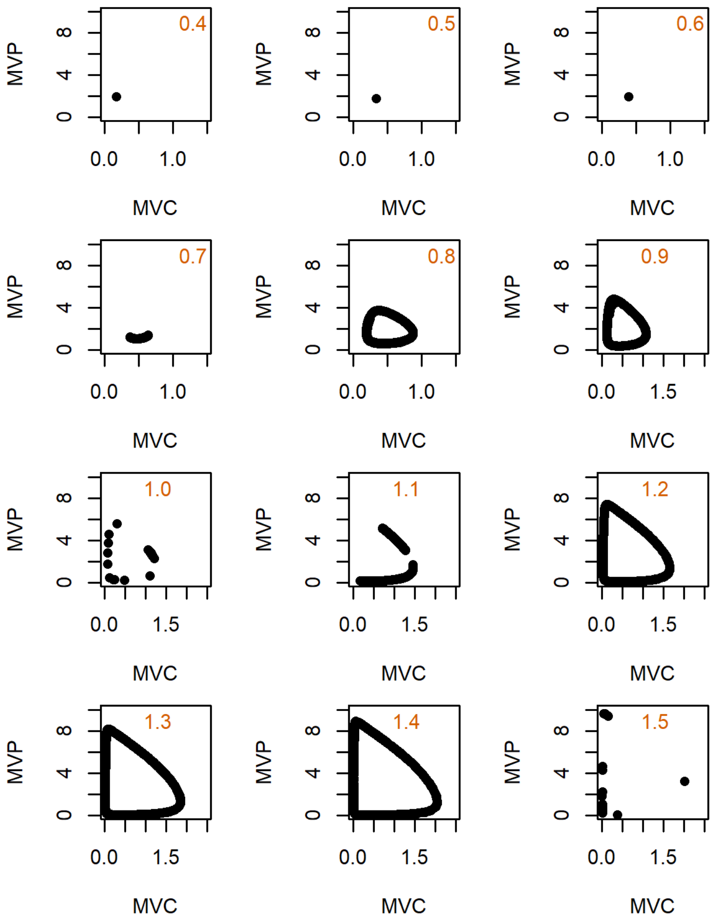

Figure 17: Poincaré plots. From upper to lower panels, increasing total nitrogen content.

$$\frac{dF}{dt} = rF\left(1 - \frac{F}{K}\right) - \frac{aF}{1 + ahF}C$$

$$\frac{dC}{dt} = \epsilon\frac{aF}{1 + ahF}C - \mu C$$

Figure 18: The Rosenzweig-MacArthur model. In the absence of predators C, prey F growth follows the logistic growth equation with growth rate r and carrying capacity K. Predation follows a Holling's type II functional response.

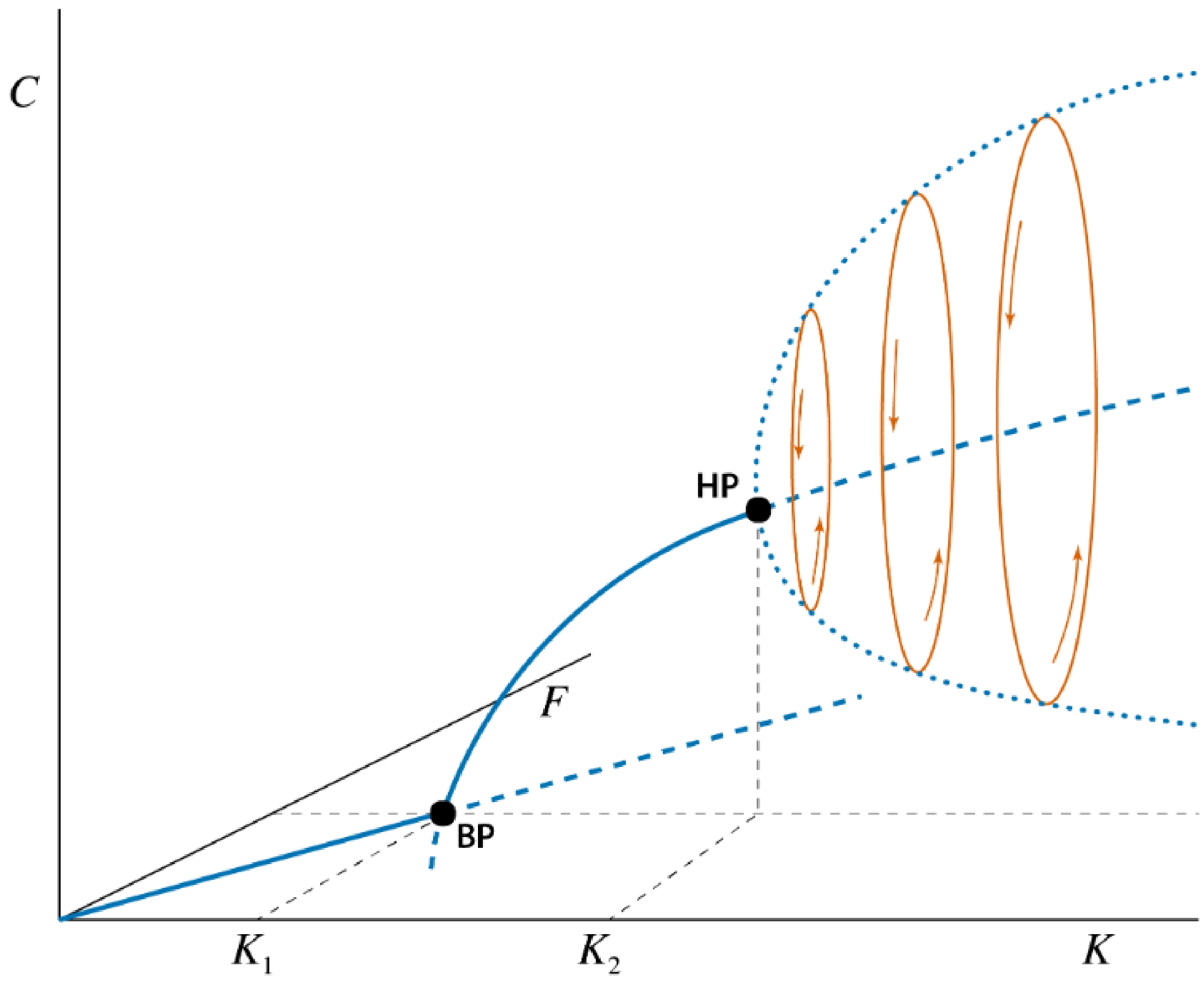

Figure 19: Bifurcation plot of the Rosenzweig-MacArthur model. From: https://staff.fnwi.uva.nl/a.m.deroos/projects/BifurcationTheory

Conclusions

- Internal dynamics are prevalent
- Paradox of enrichment holds, and already at low nutrient content point equilibrium is unstable
- Lower efficiency stabilizes
- Are additional 'tricks', such as predator-dependent functional response and a quadratic mortality term, required?

References

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