WG 1 - Resilience of global carbon and nutrient cycles.

Mick Follows

Climate, carbon and nutrient cycles appear to be subject to stabilizing feedbacks on a range of space and timescales. In the lectures I will review the implications, mechanisms and models of some of these feedbacks. In the group project we identify and explore aspects of the resilience of (one or more) elements of these systems using simple models. Idealized numerical models of ocean-atmosphere carbon and nutrient cycles will be available as possible starting points.

Stability of the Redfield Ratio.
Ocean sequestration of carbon due to the formation, sinking and remineralization of organic leads to significant ocean storage of carbon termed the soft-tissue carbon pump. The magnitude of this reservoir is controlled by the cycles of limiting resoures (N, P, Fe, ...). Redfield famously observed that the ratio of dissolved inorganic nitrogen to dissolved inorganic phosphorus is close to the N:P ratio of organic material, reflecting stabilizing feedbacks between N and P cycles which can be illustrated in simple models (e.g. Tyrell, 1999). Other models suggest regional oscillations (Monteiro and Follows, 2009) and even runaway feedbacks (Landolfi et al, 2013) in the system. The coupling and role of the iron cycle, which importantly mediates nitrogen fixation, has not yet been fully explored. Is it feasible that the nitrogen and phosphorus cycles become decoupled on the global scale? What is the role of the iron cycle in mediating the N, P and C interactions? How sensitive is the coupling to climate variations on glacial-interglacial timescales?

Climate and carbon cycle feedbacks.
Walker et al (1991) hypothesized a very long-timescale feedback between volcanism, the weathering of silicate minerals, global temperature, and atmospheric CO2 which would stabilize climate in the face of variability of volcanic emissions of CO2. The feedback depends upon the formation and burial of calcium carbonate in the oceans, a process which is now mediated by calcifying plankton that evolved relatively recently in Earth history (Zeebe and Westbroek, 2003). How significant was this innovation for the hypothesized feedback and the stability of the global carbon-cycle and climate system? What do models say about the resilience of the system to variations in volcanism?

Some background on these topics:

Redfield Ratio:
Tyrell, T. (1999) The relative influences of phosporus and nitrogen on oceanic primary production. Nature, 400, 525-531.
Landolfi, A., H. Dietze, W. Koeve, and A. Oschlies (2013) Overlooked runaway feedback in the marine nitrogen cycle: the vicious cycle. Biogeosciences, 10, 1351–1363, 2013 doi:10.5194/bg-10-1351-2013

Stabilizing Climate-Carbon Cycle Feedback
Walker, C.G., P.B. Hays and J.F. Kasting (1981) A negative feedback mechanism for the long-term stabilization of the Earth's surface temperature. J. Geophys. Res. 86(10), 9776-9782.
Zeebe, R.E., and P. Westbroek (2003) A simple model for the CaCO3 saturation state of the ocean: The 'Strangelove', the 'Neritan', and the 'Cretan' Ocean. Geochem. Geophys. Geosys.
4(12), doi:10.1029/2003GC000538

WG 2 - The mathematical foundations of resilience and its applications to the climate sciences, ecology and economics

Michael Ghil, Célian Colon and K.B.Z. Ogutu

The module presents the key mathematical concepts and methods of dynamical systems that can help understand and model resilience in all generality. In particular, the notions of internal variability, basin of attraction and tipping point will be explored through the theories of bifurcations and chaos, with applications to the climate sciences, ecology and economics.
M. Ghil will give the lectures.

Two practical sessions will complement the lectures, and allow the participants to gain hands-on experience with the theoretical concepts and basic tools.

- *Time series session.* The first practical session will be dedicated to singular spectrum analysis (SSA). This method will be applied to empirical time series in order to identify key features of periodic and quasi-periodic attractors.
- *Dynamical systems session*. In the second practical session, participants will explore the dynamical behavior of simple systems of ordinary differential equations.

C. Colon and K.B.Z. Ogutu will lead these practical sessions.

In parallel, participants will engage in a short project to reflect on the resilient behavior of coupled climate–socioeconomic systems. The content of the project will depend on the participants' interests. Potential directions are:

- How does climate forcing affect the resilience of a socioeconomic system?
- Coupling climate and economic models with internal variability.

All three instructors will guide this short project.

Relevant papers:

- Hallegatte, S., et al. "Business cycles, bifurcations and chaos in a neo-classical model with investment dynamics." *Journal of Economic Behavior & Organization* 67.1 (2008): 57-77.
- Rombouts, J., and M. Ghil. "Oscillations in a simple climate–vegetation model." *Nonlinear Processes in Geophysics* 22.3 (2015): 275-288.
- Samuelson, P. A. "Generalized predator-prey oscillations in ecological and economic equilibrium." *Proceedings of the National Academy of Sciences USA* 68.5 (1971): 980-983.

WG 3 - Consequences of individual life history for the detection of shifts between alternative states in ecological communities

André de Roos

Ecological communities are exposed to a broad range of natural and human-induced perturbations. As a consequence of such perturbations drastic, irreversible changes in community structure may occur that represent shifts between alternative, stable community states. The empirical evidence for the occurrence of alternative stable states in ecological dynamics is mounting and the shifts between such states that have been documented in particular natural systems tend to be associated with drastic consequences for biodiversity, ecosystem functioning and services. A specific example comes from the ecosystem in the northwest Atlantic Ocean, where massive overexploitation of the top predator in the system has led to a complete reorganization of the food web and a significant drop in the harvestable fish biomass. Resilience in ecological systems is therefore to quite an extent focused on protecting against such shifts between alternative stable states in ecological communities and on the detection of early warning signals that indicate their imminent occurrence (Scheffer et al., 2009).

A major shortcoming of the ecological theory on shifts between alternative stable community states is that it is based on mathematical models that ignore the life history of individual organisms. These so-called, unstructured models therefore resemble models of physical or chemical systems of interacting particles and disregard the very aspect that distinguishes individual organisms from such particles. The analysis of ecological models that do account for individual life histories suggest that the associated complexity increases the scope for alternative community states to occur, because stable community states can differ from each other not only in the abundance or density of the constituting populations, but also in the composition of these populations. A second, so-far little explored issue with regards to individual life history and shifts between alternative community states is that accounting for a life history introduces time-lags in the ecological dynamics as well as an element of memory that may affect our capacity to develop early warning signals for the shifts between such alternative community states (Boerlijst et al., 2013).

The general aim of this project is to investigate whether or not accounting for individual life history changes our capacity to detect early warning signals for imminent shifts between alternative community states. A possible approach would be studying the dynamics of one or two published models for the population dynamics of size-structured ecological communities (as, for example, reported in de Roos & Persson, 2002; see also Nisbet et al., 2016) exposed to environmental stochasticity to assess to what extent the methodologies developed for unstructured ecological models apply in case of size-structured models as well.

Relevant literature

Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., et al. (2009). Early-warning signals for critical transitions. Nature, 461(7260), 53–59. http://doi.org/10.1038/nature08227

M.C. Boerlijst, T. Oudman & A.M. de Roos, 2013. Catastrophic collapse can occur without early warning: examples of silent catastrophes in structured ecological models. PLOS ONE 8 (4): e62033. http://doi.org/10.1371/journal.pone.0062033.

A.M. de Roos & L. Persson, 2002. Size-dependent life-history traits promote catastrophic collapses of top predators. Proc. Natl. Acad. Sciences 99(20): 12907-12912.

Nisbet, R. M., Martin, B. T., & de Roos, A. M. (2016). Integrating ecological insight derived from individual-based simulations and physiologically structured population models. Ecological Modelling, 326, 101–112. http://doi.org/10.1016/j.ecolmodel.2015.08.013

WG 4 - Agroecology: (how) does biodiversity promote resilience?

David Claessen, Pierre-Antoine Précigout and Corinne Robert

In this working group, the focus is on the idea - widespread in the context of agroecology - that the resilience of agroecosystems depends on the level of “biodiversity”. Here biodiversity may refer to diversity in terms of the number cultivated species and cultivars, the number of natural species in the agroecosystems, but also in terms of functional diversity (such as the number of trophic levels). In order to study the implications of this hypothesis, and to critically analyze its underlying assumptions, we will study the dynamics of a simple model of an agro-ecosystem in terms of its trophic structure. The model represents the cycling of matter across a system consisting of nutrients (N), plants (P), herbivores (H), predators (E) and dead organic material (D). Specifically, the model can account for the seasonally forced nature of crop dynamics due to sowing and harvesting, which is not necessarily the case for other plant species in the agroecosystems. The model can also account for nitrogen fixation by legumes, and the loss of nutrients by washing out to the deep soil. In the working group sessions, the model can be extended in different directions: include multiple species at different trophic levels, include different nutrients (nitrogen, phosphorus, other elements); include water in the soil and the effect of plants on water retention.

An important part of the working group will be to discuss the question of how to define and quantify “resilience” in the contexts of agroecology and in particular for this modeling approach.

Possible questions that can be investigated during the working group are:

- Does higher biodiversity make an agro-ecosystem less dependent on chemical input (fertilization, pesticides)?
- Does a biodiverse agroecological system stock more carbon than industrial agriculture?
- Does high biodiversity make an agroecosystems more resilient against emergent crop pathogens? Against water stress? Against soil degradation?
- What is the specificity of an agro-ecosystem compared to a natural ecosystem and how does this influence resilience?

PDFs of the references below are available from the CERES website.

References

Altieri, M.A., Nicholls, C.I., Henao, A., and Lana, M.A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development* 35**,** 869-890. doi: 10.1007/s13593-015-0285-2.

Bohan, D.A., Raybould, A., Mulder, C., Woodward, G., Tamaddoni-Nezhad, A., Bluthgen, N., Pocock, M.J.O., Muggleton, S., Evans, D.M., Astegiano, J., Massol, F., Loeuille, N., Petit, S., and Macfadyen, S. (2013). Networking Agroecology. 49**,** 1-67. doi: 10.1016/b978-0-12-420002-9.00001-9.

Tixier, P., Peyrard, N., Aubertot, J.-N., Gaba, S., Radoszycki, J., Caron-Lormier, G., Vinatier, F., Mollot, G., and Sabbadin, R. (2013). "Modelling Interaction Networks for Enhanced Ecosystem Services in Agroecosystems," in *Advances in Ecological Research, Vol 49: Ecological Networks in an Agricultural World,* eds. G. Woodward & D.A. Bohan.), 437-480.