

Atelier Méthodes quantitatives en environnement : **Modélisation**

Retroactions interdisciplinaires

Vincent Le Bourlot, Andreas Groth, Michael Ghil, Jean Roux, David Claessen



TERRE

La Terre voit venir le changement d'ère

9 août 2012 à 21:46

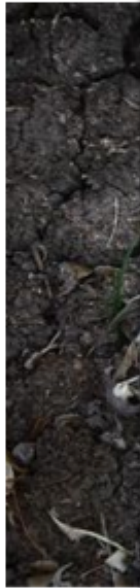


Les restes d'une carpe au fond d'un lac asséché par la canicule dans la réserve de faune sauvage de Cheyenne Bottoms, dans le Kansas, le 7 août 2012. (Photo Jeff Tuttle. Reuters)

ANALYSE ♦ Selon «Nature», l'action de l'homme sur son environnement mène la planète à un point de basculement. Le

La Terre d'ère

9 août 2012 à



Les restes d'une
faune sauvage
Tuttle. Reute

- A +

Dans les crises passées, c'est la biogéochimie de la Terre, des éruptions volcaniques ou une météorite gigantesque qui ont déclenché des changements radicaux. Cette fois, les chercheurs pointent du doigt l'homme. Pour le groupe de Tony Barnosky, paléo-écologiste, qui a coordonné les travaux des chercheurs, nous sommes *«suffisamment puissants»* pour faire basculer les conditions de vie sur Terre, en modifiant radicalement des écosystèmes et des climats locaux. *«En clair, ce sont les comportements et les besoins humains qui précipitent le changement d'état»*, d'après Steve Carpenter, de l'Université du Wisconsin.

Ces changements d'état peuvent être infimes et locaux, se limiter à un lac, un étang... *«Ceux-là, on les comprend assez bien. Mais les plus gros points de basculement sont encore difficiles à cerner»*, explique Marten Scheffer, pionnier de la recherche dans ce domaine. Surtout, Scheffer n'est pas convaincu qu'un seul point de basculement est imminent. *«Il y a eu d'énormes points de basculement planétaires dans le passé et il y en a en cours. La différence, aujourd'hui, c'est qu'on les voit arriver...»*

Deux choses provoquent un changement d'état : l'effet de seuil ou l'effet de masse. Le premier est difficile à prévoir, puisque le seuil critique est atteint par palier, et qu'on ne connaît jamais la valeur de la criticité d'avance. En revanche, l'effet de masse ne vient jamais par surprise : comme, par exemple, la destruction d'une forêt par un bulldozer. Or, les humains modifient la composition des espèces locales et les fonctions des écosystèmes, provoquant des changements à petite échelle, lesquels combinés les uns aux autres forment une cascade alimentant une bascule plus globale.

«L'aspect irréversible me laisse dubitatif»

9 août 2012 à 20:56

INTERVIEW ◀ Robert Barbault dirige le département d'écologie et de gestion de la biodiversité au Muséum d'histoire naturelle :

Par LAURE NOUALHAT, ELIANE PATRIARCA

«Cette étude change des approches fragmentaires habituelles. C'est un article intéressant. Je pense qu'on y fera référence dans le futur car c'est une vue d'ensemble, une vision écologique qui montre où va le monde. L'idée clé, c'est cette notion de seuils avec effet de bascule que l'on connaissait pour les écosystèmes : cette fois, la notion est généralisée à l'ensemble de la Terre et s'appuie sur le fait qu'aujourd'hui c'est l'espèce humaine qui est le moteur principal des grandes évolutions de la planète.

«Cette étude est un plaidoyer pour mobiliser des efforts de recherche, notamment pour parvenir à identifier les signaux précurseurs. Elle souligne aussi que des phénomènes observés localement (désertification, hausse des températures, déforestation, pollution...) se propagent ou ont un impact ailleurs dans le monde, du fait de notre mode d'existence. On peut donc parler d'un écosystème planétaire.

«En revanche, je reste dubitatif lorsqu'ils prennent pour référence les transitions majeures comme la crise du créacé tertiaire ou la grande glaciation. Est-on vraiment dans des conditions comparables ? Ces transitions se sont produites sur de très grandes échelles de temps. Aujourd'hui, il y a une accélération sous la pression des activités humaines. C'est toujours LA question : est-on dans la 6^e grande crise d'extinction ? Avant, l'homme n'était pas impliqué. Or, là, nous sommes le moteur du phénomène, ce qui, en théorie, laisse entre nos mains la possibilité de redresser la barre. L'irréversibilité du processus me laisse donc dubitatif.»

Approaching a state shift in Earth's biosphere

Anthony D. Barnosky^{1,2,3}, Elizabeth A. Hadly⁴, Jordi Bascompte⁵, Eric L. Berlow⁶, James H. Brown⁷, Mikael Fortelius⁸, Wayne M. Getz⁹, John Harte^{9,10}, Alan Hastings¹¹, Pablo A. Marquet^{12,13,14,15}, Neo D. Martinez¹⁶, Arne Mooers¹⁷, Peter Roopnarine¹⁸, Geerat Vermeij¹⁹, John W. Williams²⁰, Rosemary Gillespie⁹, Justin Kitzes⁹, Charles Marshall^{1,2}, Nicholas Matzke¹, David P. Mindell²¹, Eloy Revilla²² & Adam B. Smith²³

Localized ecological systems are known to shift abruptly and irreversibly from one state to another when they are forced across critical thresholds. Here we review evidence that the global ecosystem as a whole can react in the same way and is approaching a planetary-scale critical transition as a result of human influence. The plausibility of a planetary-scale 'tipping point' highlights the need to improve biological forecasting by detecting early warning signs of critical transitions on global as well as local scales, and by detecting feedbacks that promote such transitions. It is also necessary to address root causes of how humans are forcing biological changes.

Humans now dominate Earth, changing it in ways that threaten its ability to sustain us and other species¹⁻³. This realization has led to a growing interest in forecasting biological responses on all scales from local to global⁴⁻⁷.

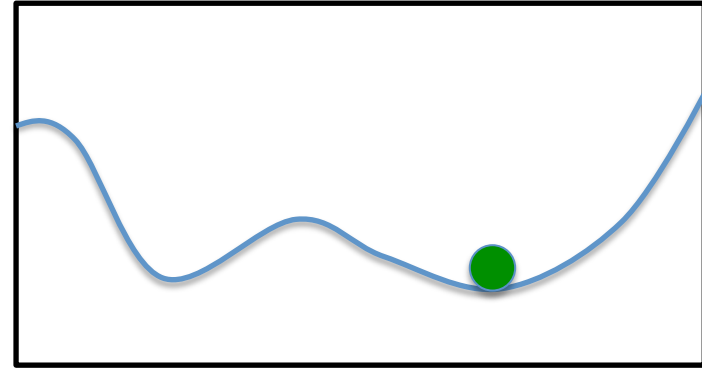
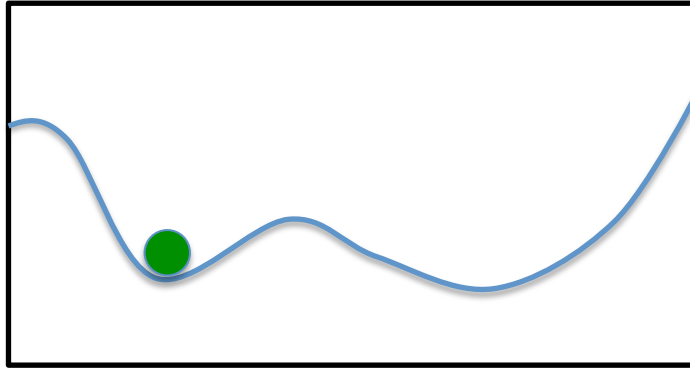
However, most biological forecasting now depends on projecting recent trends into the future assuming various environmental pres-

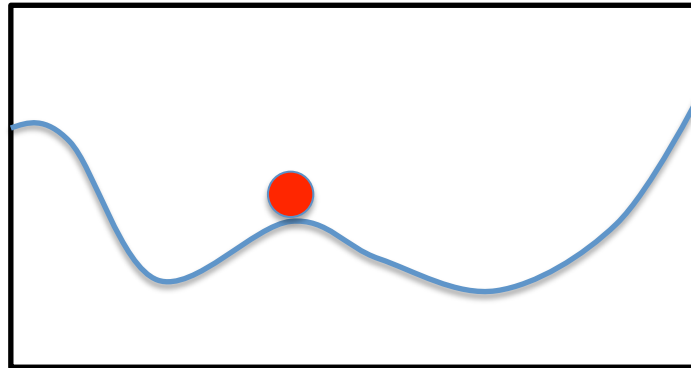
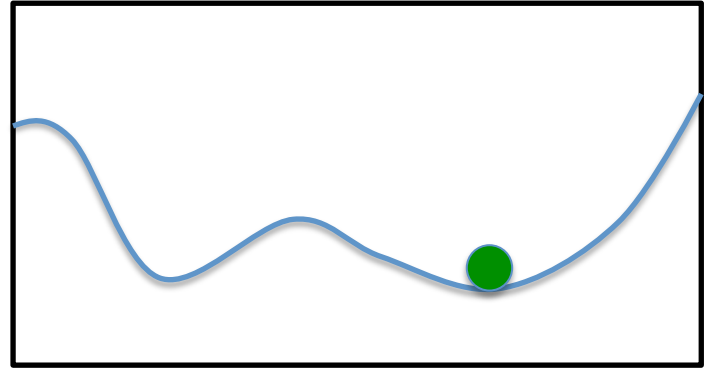
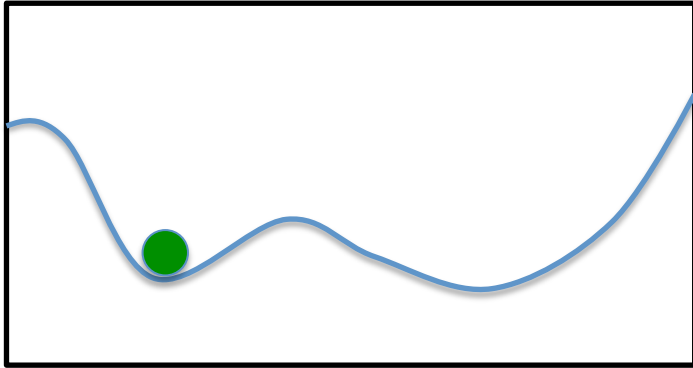
necessary to address the root causes of human-driven global change and to improve our management of biodiversity and ecosystem services^{3,15-17,19}.

Basics of state shift theory

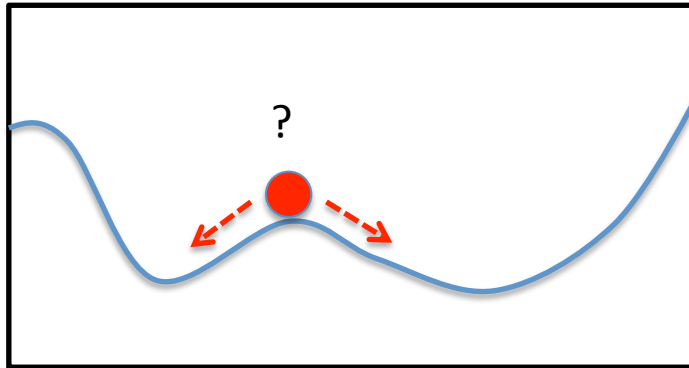
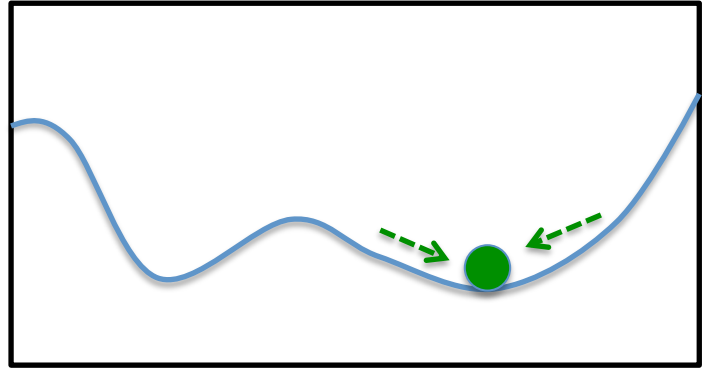
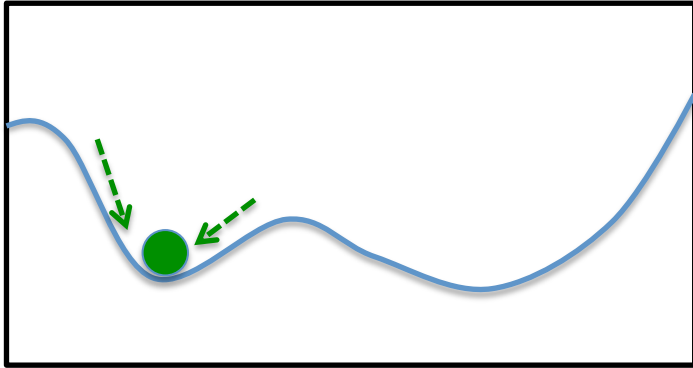
It is now well documented that biological systems on many scales can shift rapidly from an existing state to a radically different state¹².

Alternative stable states

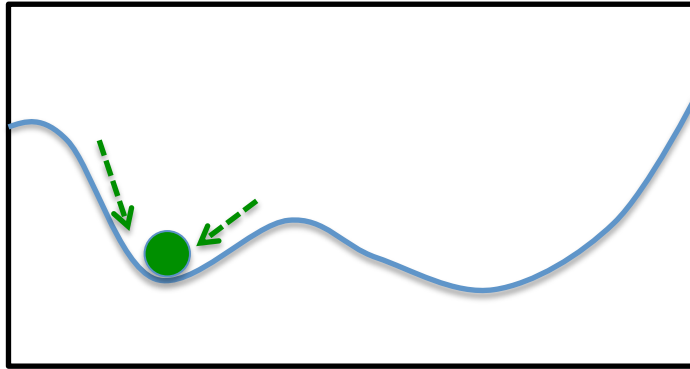




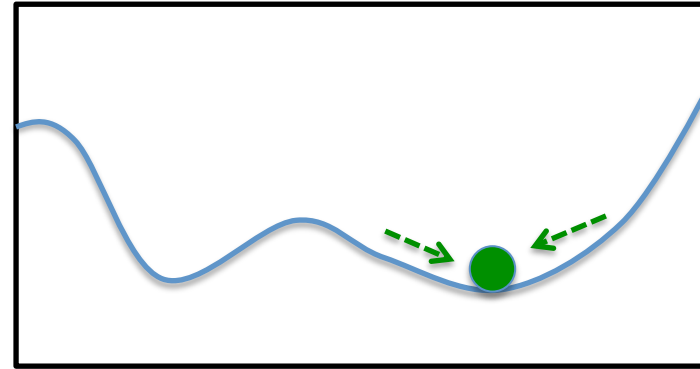
Unstable state



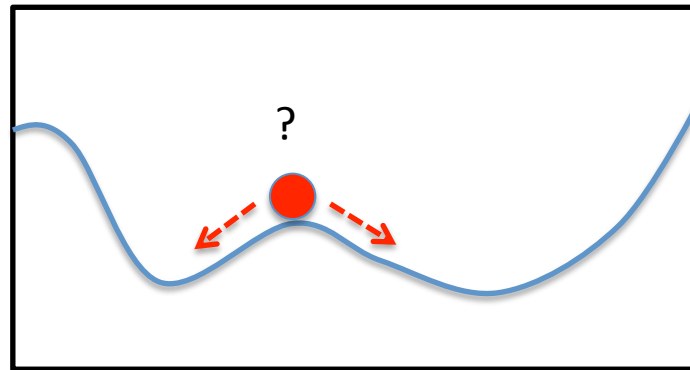
Stable equilibrium A



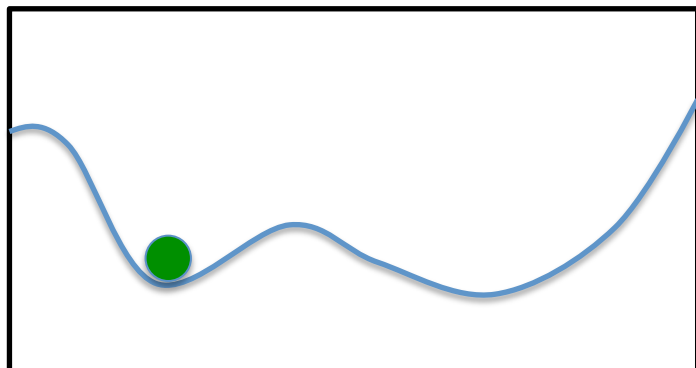
Stable equilibrium B



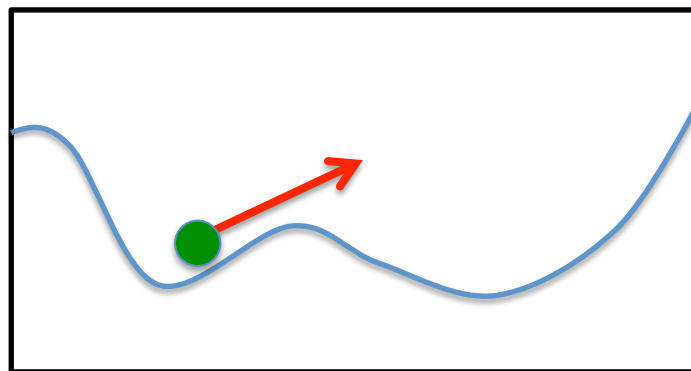
Unstable equilibrium



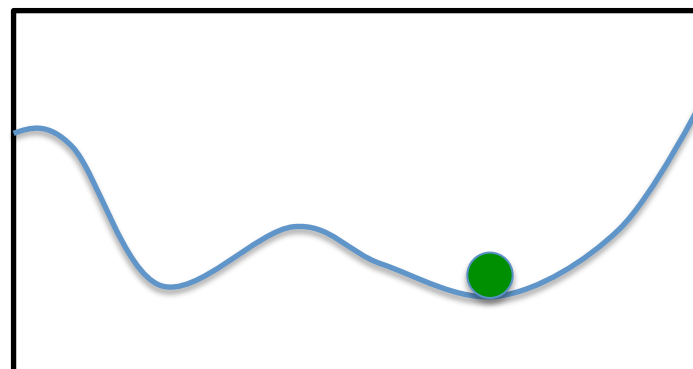
State A



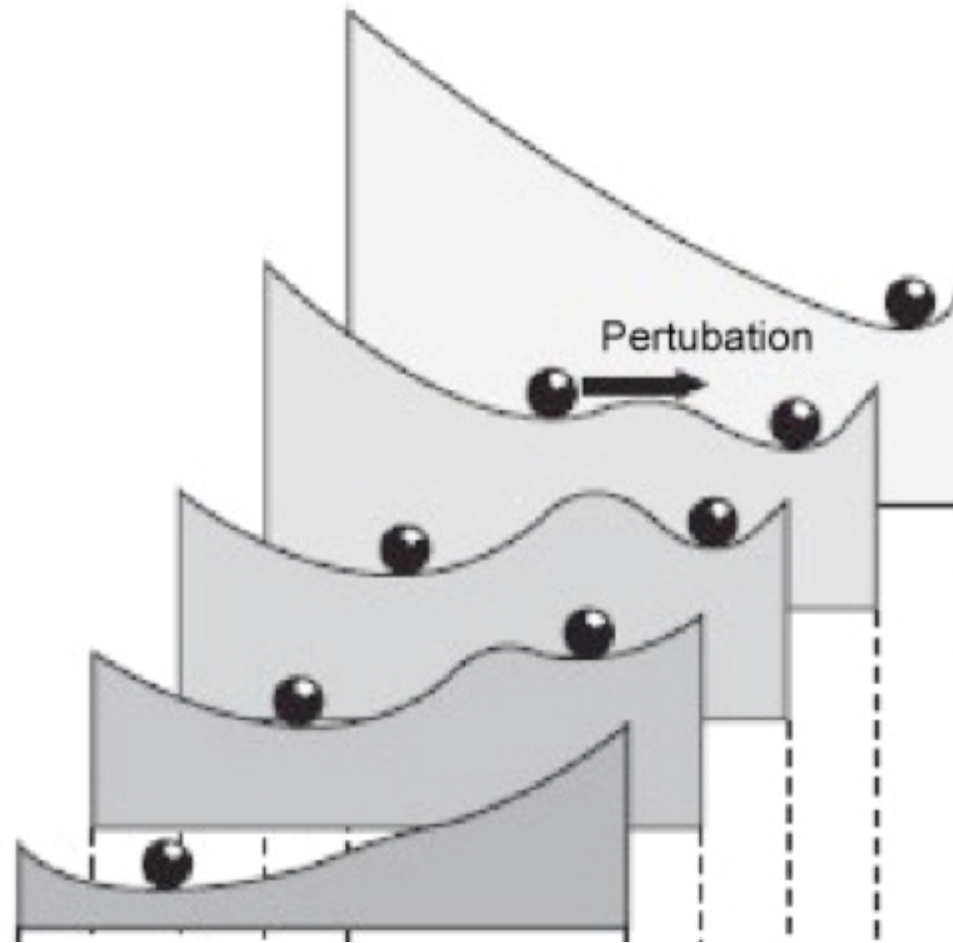
Perturbation



State B

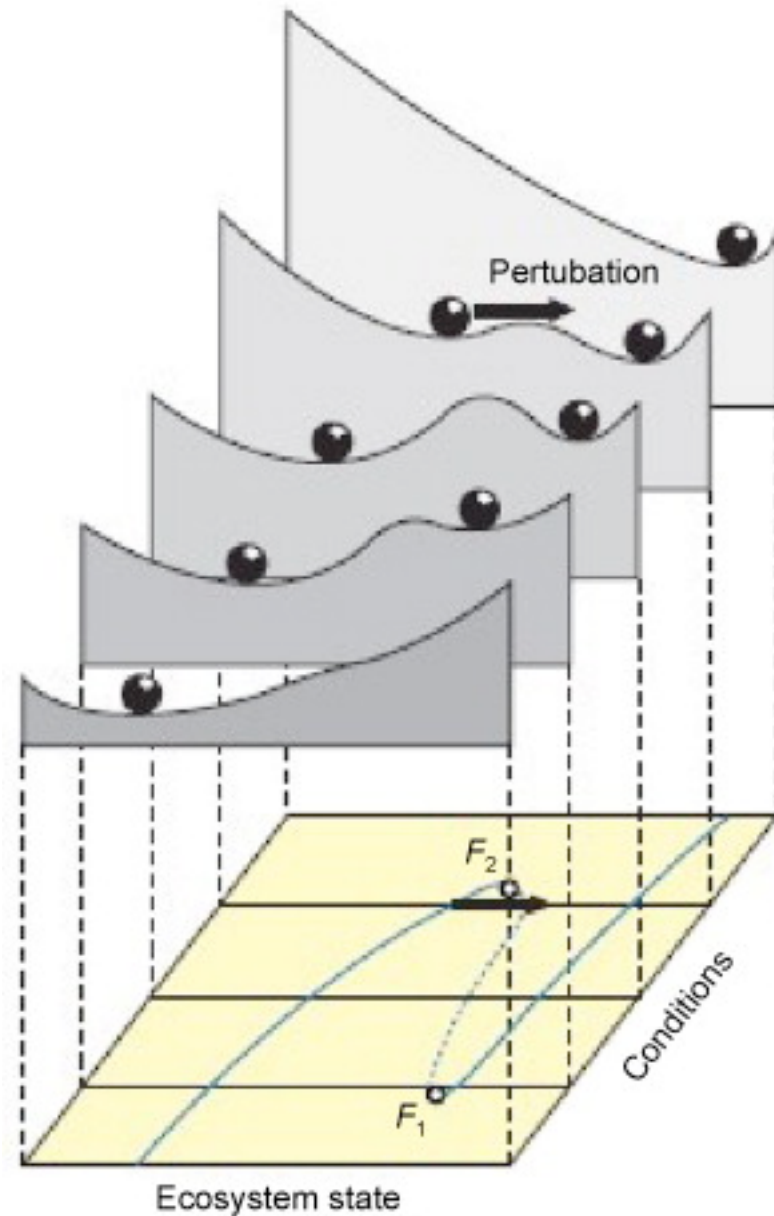


Le “paysage” dépend des paramètres du système



“Bifurcation pli” en version visuelle

- Plotter la position de l'équilibre en fonction du paramètre
- La courbe est pliée



Approaching a state shift in Earth's biosphere

Anthony D. Barnosky^{1,2,3}, Elizabeth A. M. Sibly⁴, John Harte^{5,10}, Alan Geerat Vermeij⁶, John W. Williams⁷, David P. Mindell⁸, Eloy Revilla⁹ & A. W. D. Lenoir¹¹

Localized ecological systems are likely to approach critical thresholds. Here we show that as the Earth approaches a planetary-scale tipping point, the transitions on global as well as local scales necessary to address root causes

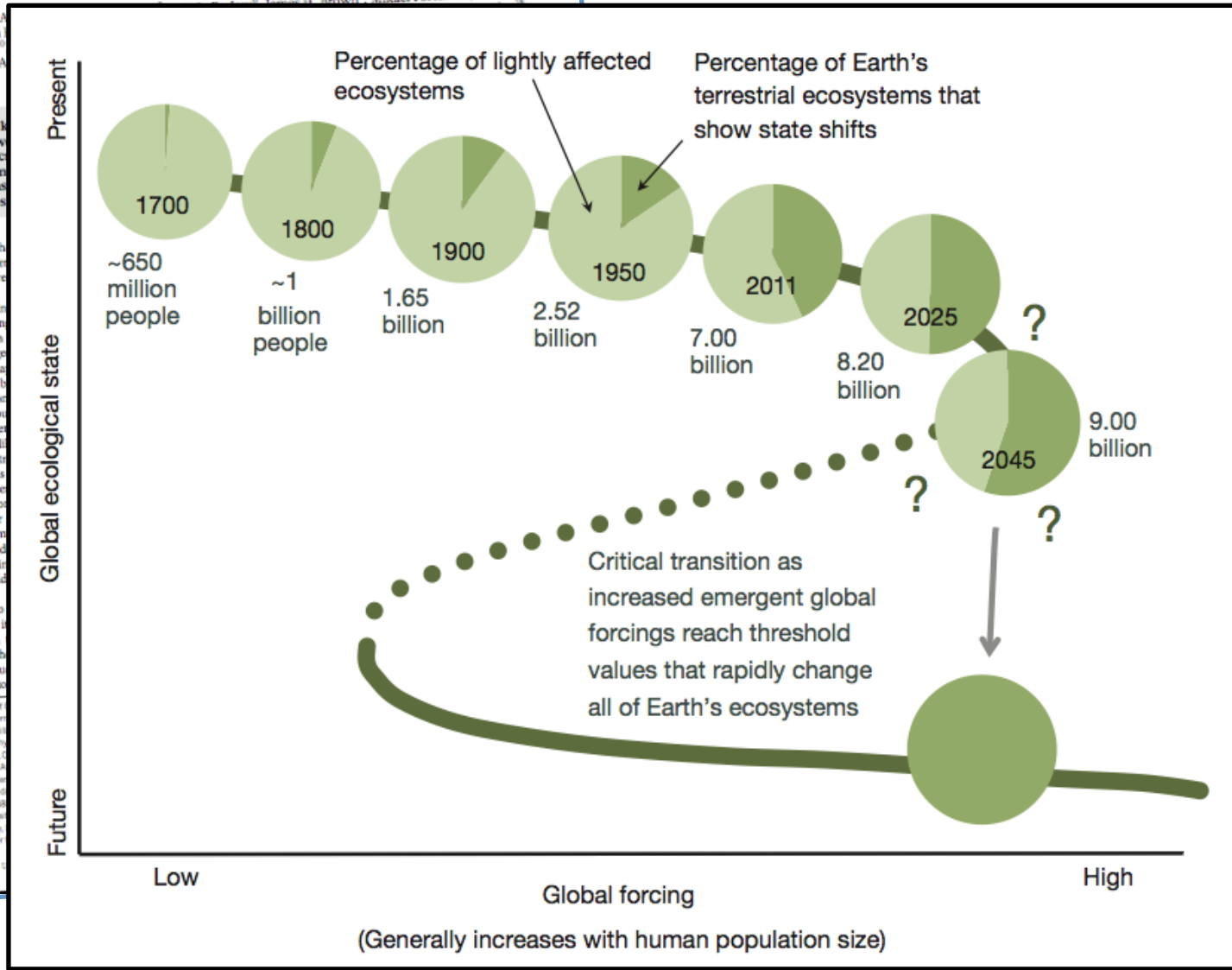
Humans now dominate Earth, and their activities have led to a growing interest in forecasting future trends in the biosphere across all scales from local to global.

However, most biological forecasting methods, such as species distribution models, or on using species distribution changes may alter present observations and recognize that relying solely on such data to characterize fully the range of likely future changes is especially because complex interactions and feedback effects are not taken into account.

Particularly important are recent observations of 'state shifts' caused by threshold effects are likely to be abrupt and irreversible, which abruptly override the gradual effects. Although most previous observations of state shifts have been theoretical or conceptual, localized ecological systems over short time scales have shown critical transitions that operate over decadal to centennial timescales. Here we summarize evidence for global-scale critical transitions that have occurred rarely, and that humans are now forcing to occur more frequently.

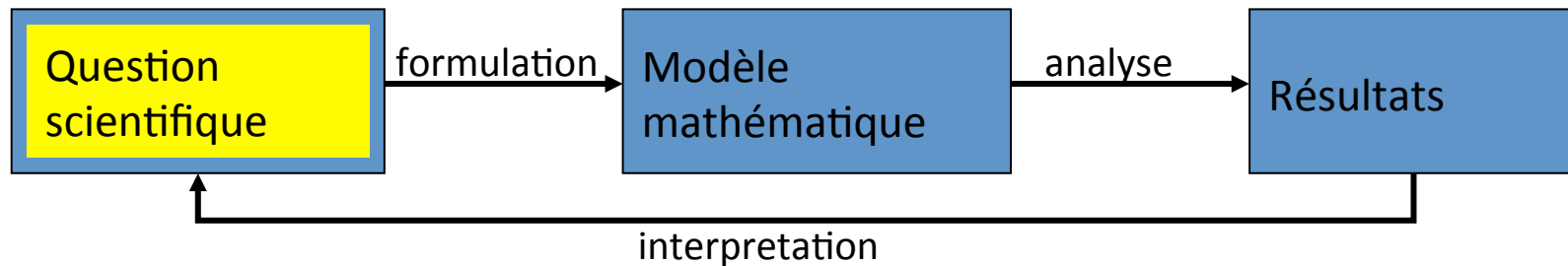
Two conclusions emerge. First, to avoid adverse impacts on humanity, it is essential to anticipate critical transitions at the planetary scale and understand the mechanisms that drive them. Second, as well as concluding that a global-scale state shift, or at least a

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Deux objectifs

- Conceptuel: traduction problématique \leftrightarrow modèle
- Outil: systèmes dynamiques & analyse de bifurcations



Modélisation

- Objectif: répondre à une question
- Quelles questions nécessitent de la modélisation?
- Système
 - Choix de variables (et structure, dimensions)
 - Choix de paramètres
 - Temps discrète / continue

Modélisation écologique

- Dynamique des écosystèmes
 - Populations, communautés, écosystèmes
 - Dynamique vs évolution
- Ici: retroactions positive entre « écologie » et « géosciences »
 - Interactions plante-sol
 - Dynamique resultante
 - *Spatial patterns*
 - Implication pour l'exploitation humaine ?
 - *Tragedy of the commons*

Regular pattern formation in real ecosystems

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Localized ecological interactions can generate striking large-scale spatial patterns in ecosystems through spatial self-organization. Possible mechanisms include oscillating consumer–resource interactions, localized disturbance–recovery processes and scale-dependent feedback. Despite abundant theoretical literature, studies revealing spatial self-organization in real ecosystems are limited. Recently, however, many examples of regular pattern formation have been discovered, supporting the importance of scale-dependent feedback. Here, we review these studies, showing regular pattern formation to be a general phenomenon rather than a peculiarity. We provide a conceptual framework explaining how scale-dependent feedback determines regular pattern formation in ecosystems. More empirical studies are needed to better understand regular pattern formation in ecosystems, and how this affects the response of ecosystems to global environmental change.

Spatial self-organization

Theoretical ecologists increasingly emphasize that ecosystems can reveal spatial self-organization. Spatial self-organization is the process where large-scale ordered spatial patterns emerge from disordered initial conditions through local interactions. This process is key to understanding ecological stability and diversity [1]. Causal mechanisms explaining spatial self-organization include oscillating consumer–resource interactions leading to spiral waves [2,3], localized disturbance–recovery processes resulting in power laws in the geometry of clusters [4,5], and scale-dependent feedback with ensuing regular patterns [6]. Despite a significant body of theoretical literature on each of these mechanisms [1], there are only a few studies describing spatial self-organization in real ecosystems.

Recently, however, a large body of literature has reported on regular pattern formation across real ecosystems with striking cross-ecosystem similarities. Here, we review these studies to show that scale-dependent feedback between organisms and their environment can explain regular pattern formation in all of these ecosystems. After introducing the principle of scale-dependent feedback, we report on real ecosystems in which scale-dependent feedback leads to regular pattern formation. We uncover the prerequisite of long-distance negative feedback as a unifying principle for regular pattern formation in ecosystems. We also provide possible ways to

measure this mechanism. Finally, we discuss the implications of our conceptual framework for future research, which is needed to understand and predict the dynamics of these ecosystems, including their emergent properties, in relation to global environmental change.

Scale-dependent feedback

Ecosystems consist of organisms and the environment, which interact with each other. These interactions can impose various feedbacks upon the organisms and the environment. The feedback can be negative, for example when organisms deplete resources, leading to competition. Positive feedback can also occur, for example if organisms help others to survive through facilitation, by modifying the environment. If positive and negative feedbacks occur at different spatial scales (i.e. scale-dependent feedback), they might invoke regular pattern formation in ecosystems, even in the absence of underlying environmental heterogeneity [6].

Glossary

Localized disturbance–recovery processes: disturbance occurs primarily close to a site already disturbed (e.g. by wind) and recovery takes place primarily close to a site that is occupied by organisms (e.g. by local seed dispersal).

Long-distance negative feedback: ecological interactions resulting in a net negative feedback between organisms and their environment at a particular distance from the organisms.

Long-range competition: the process where organisms, by depleting resources, constrain the establishment and survival of other organisms over a long range.

Oscillating consumer–resource interactions: cyclic dynamics in a predator population and its prey, caused by strong feeding interactions between the two.

Power laws: any polynomial relationship that exhibits the property of scale invariance, implying that the relation is the same at a range of scales. In the case of the geometry of clusters of organisms, a decreasing linear relation occurs between cluster size and the frequency at which clusters of this size are found when plotted on a double logarithmic scale.

Regular patterns: spatially periodic patterns with a characteristic cluster size (e.g. the spotted coats of leopards).

Resilient: an ecosystem is resilient if it remains in the same domain of attraction and quickly returns to the same state after a disturbance.

Resistant: an ecosystem is resistant if it can withstand environmental change and still remain in the same state.

Scale-dependent feedback: the strength and sign of a feedback between organisms and their environment varies with distance.

Short-distance positive feedback: ecological interactions resulting in a net positive feedback between organisms and the environment near the organisms.

Short-range facilitation: the process where organisms, by creating favourable environmental conditions over a short range, help the establishment and survival of other organisms close-by.

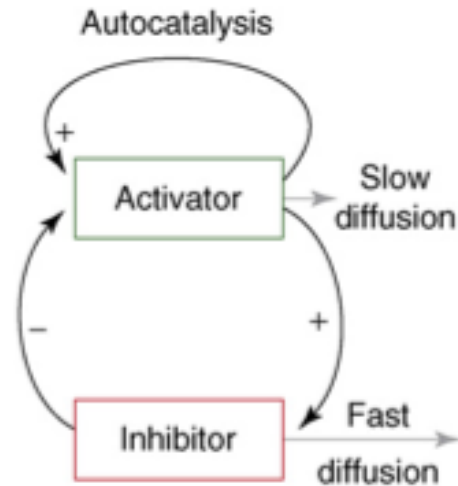
Spatial self-organization: the process where large-scale ordered spatial patterns emerge from disordered initial conditions through local interactions.

Spiral waves: spirals that rotate over time around either meandering or stationary cores.

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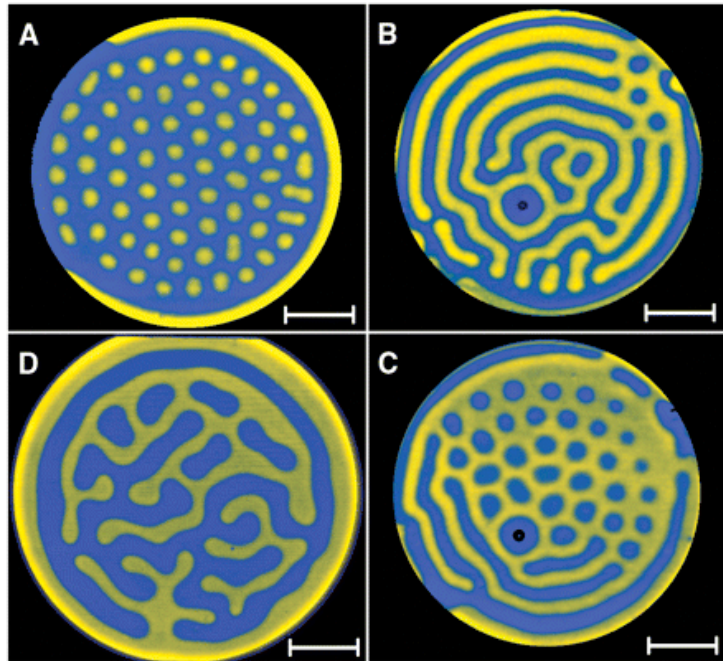
- Rietkerk & Van de Koppel (2008) Trends in Ecology and Evolution Vol.23 No. 3

(a)

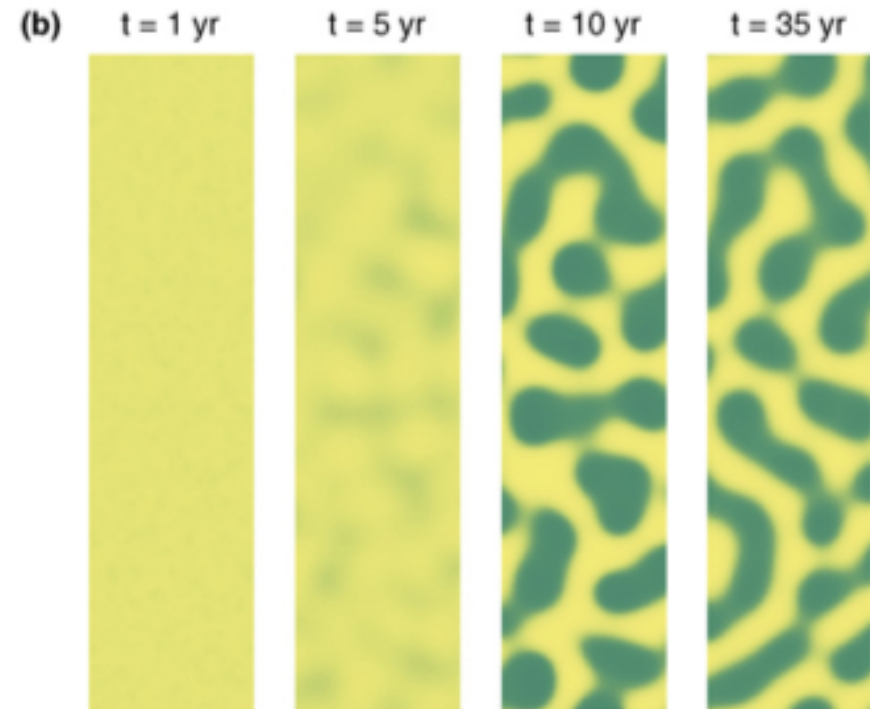
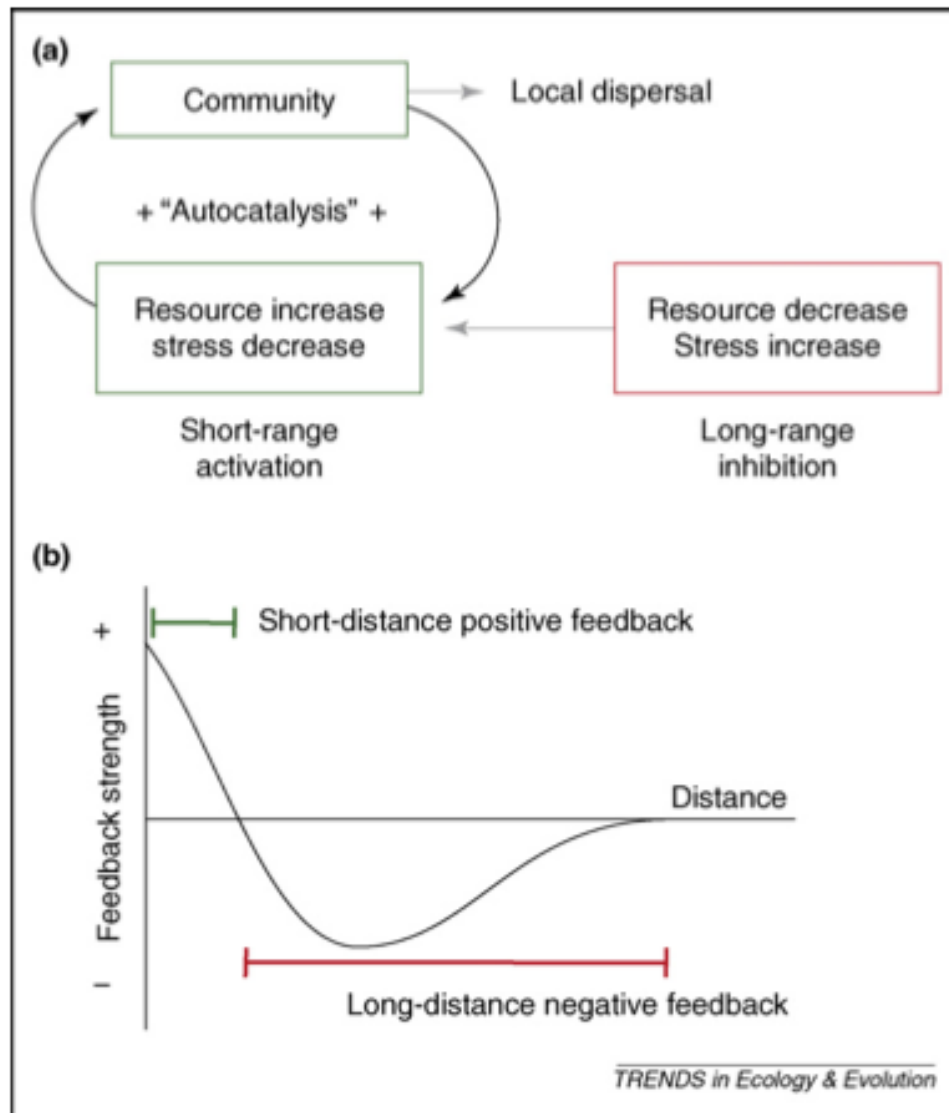


Turing patterns

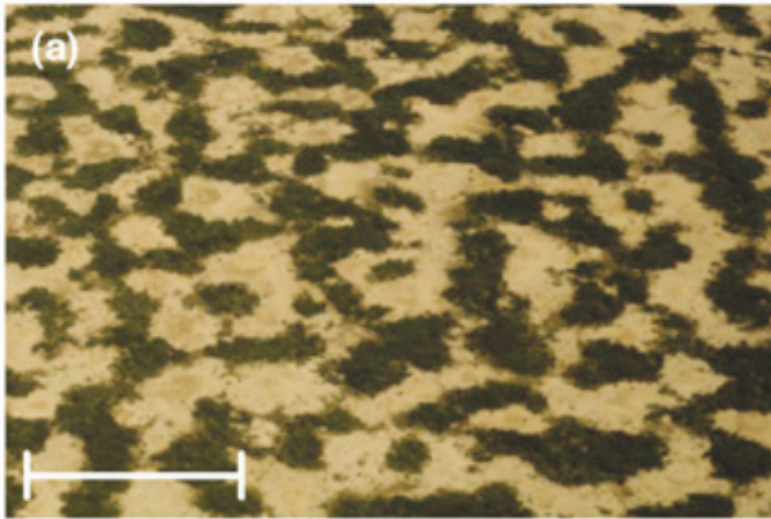
- Alan Turing (1912-1954)
- Autocatalysis in activator-inhibitor system
 - More A \rightarrow more A produced
 - But also more I, inhibition
- A and I diffuse at different rates
- Turing: if I diffuses faster than A \rightarrow spatial patterns
- Scale dependent feedback of A and I : positive feedback dominates at short distance, whereas negative feedback dominates at longer distance



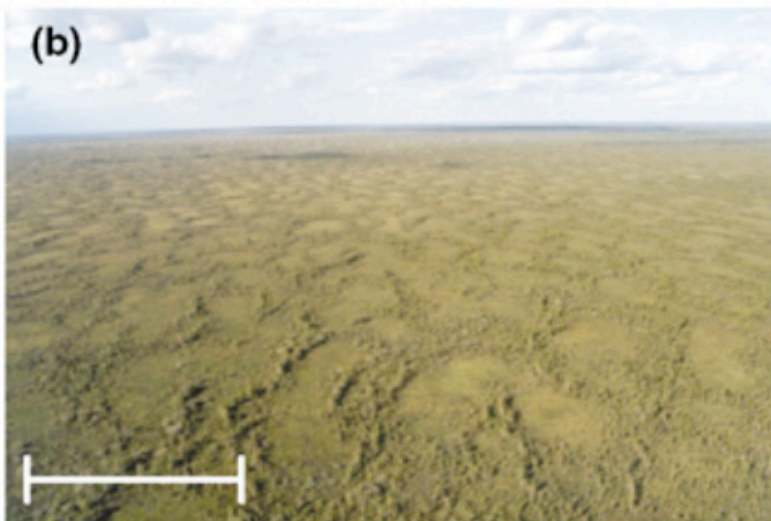
Scale dependent feedback in ecology



Retroactions positive, catastrophes, transitions, « spatial patterns »



(a) Labyrinth pattern of bushy vegetation in Niger (scale = 100 m).

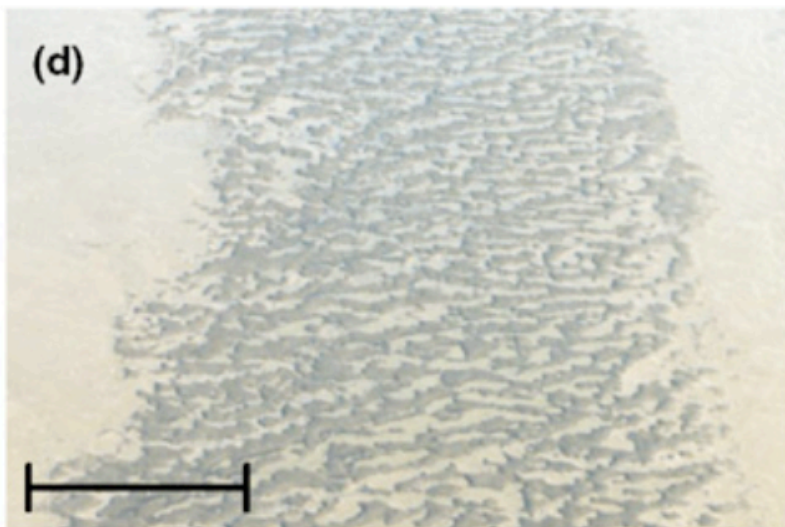


(b) Regular maze patterns of shrubs and trees in West Siberia (scale = 100 m).

Retroactions positive, catastrophes, transitions, « spatial patterns »

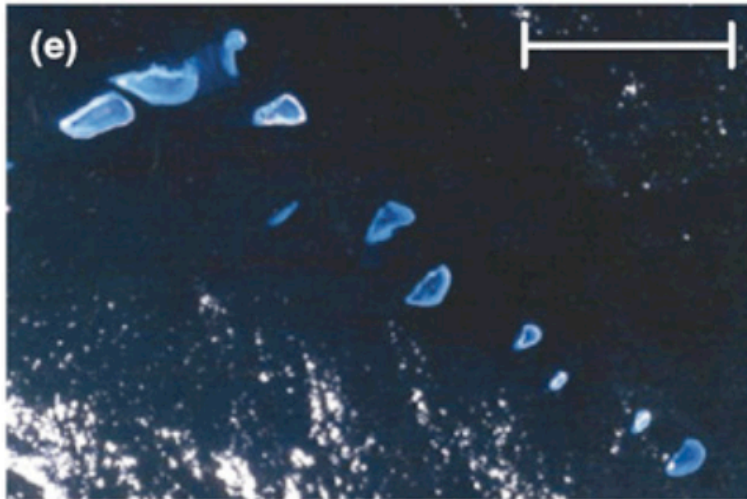


(c) Spotted pattern of isolated tree patches in Niger (scale = 200 m).



(d) Patterned mussel bank in the Wadden Sea, the Netherlands (scale = 50 m).

Retroactions positive, catastrophes, transitions, « spatial patterns »

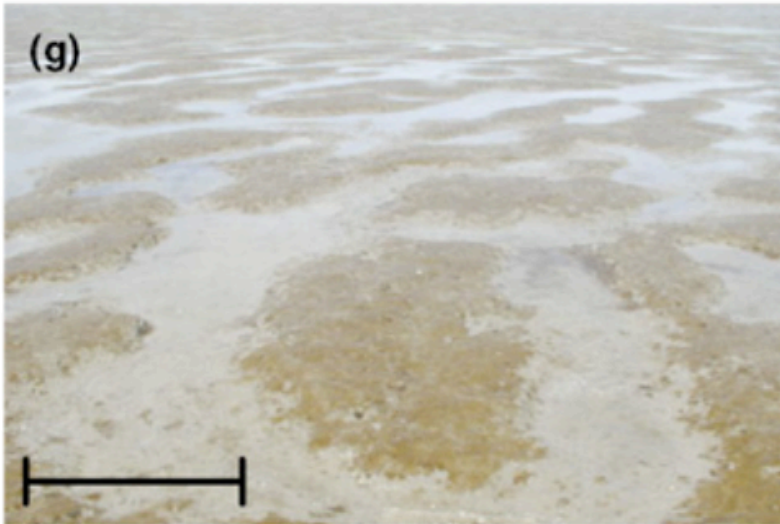


(e) Reef islands oriented in series along the predominating direction of large-scale currents in Australia (scale = 20 km).

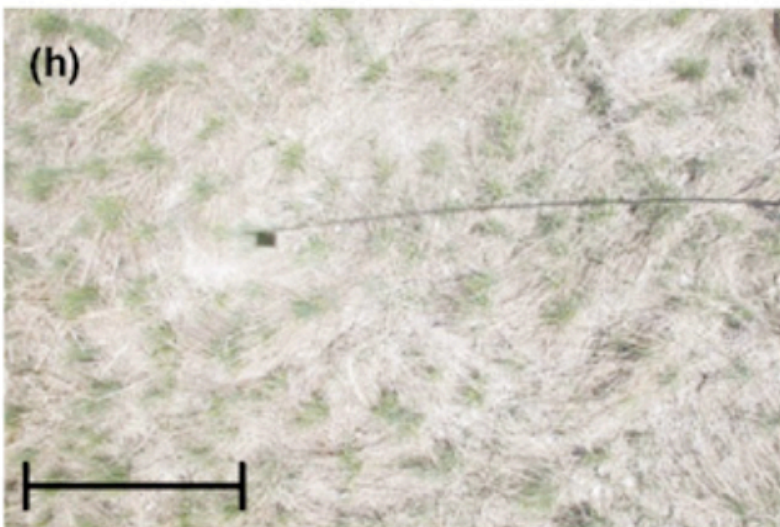


(f) Striped pattern of tree lines and snow deposition in ribbon forests in USA

Retroactions positive, catastrophes, transitions, « spatial patterns »



(g) Labyrinth pattern of marine benthic diatoms in the Netherlands (scale = 1 m).



(h) Regular spaced tussocks (touffes d'herbe) of the sedge *Carex stricta* (scale = 2 m).

A simple model to explain all this?

