

Limites planétaires: concept et matière à réflexion pour un futur soutenable

Théo VISCHEL

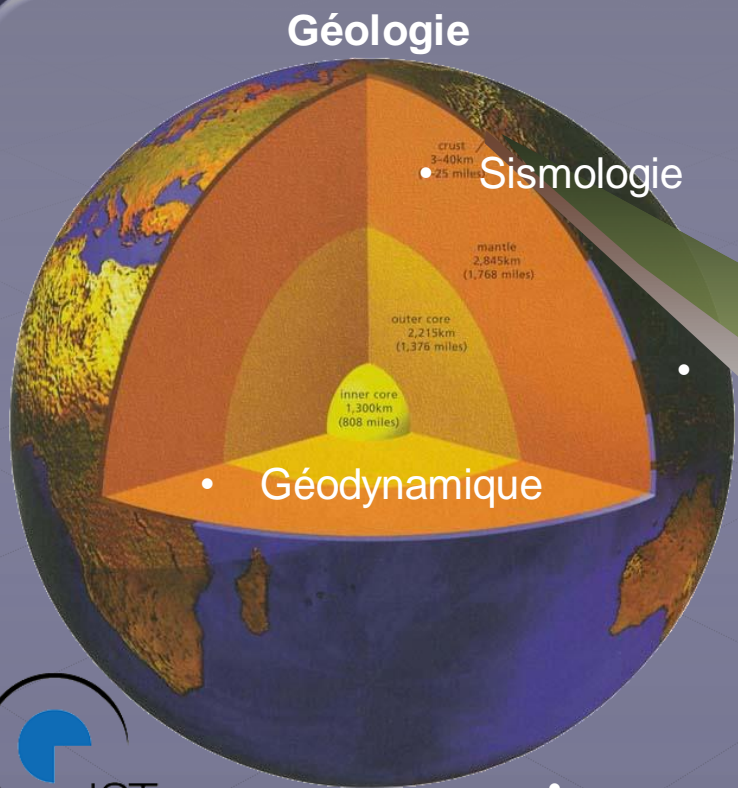
Enseignant-Chercheur Professeur en Hydrologie

Université Grenoble Alpes – Institut des Géosciences de l'Environnement

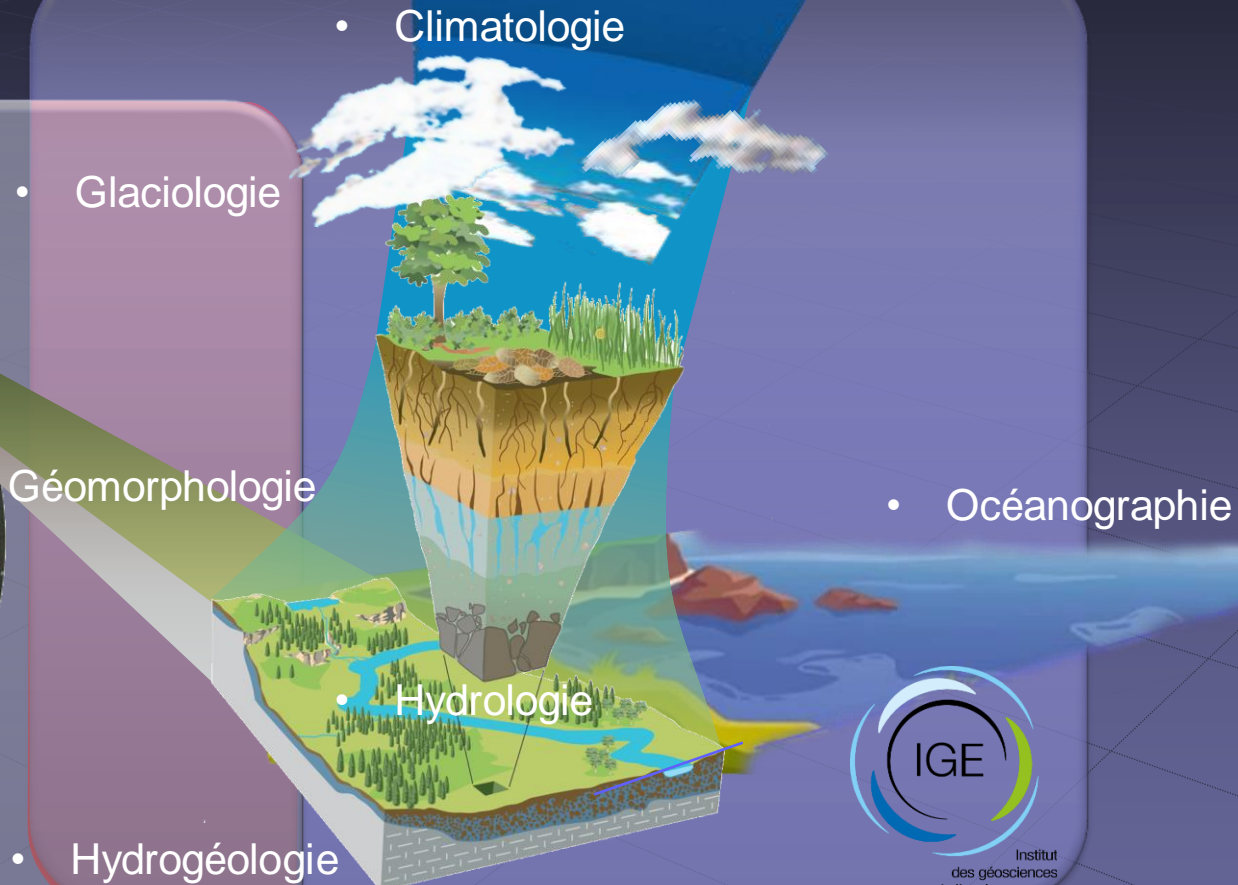


50 nuances de **Greyosciences**

Terre interne

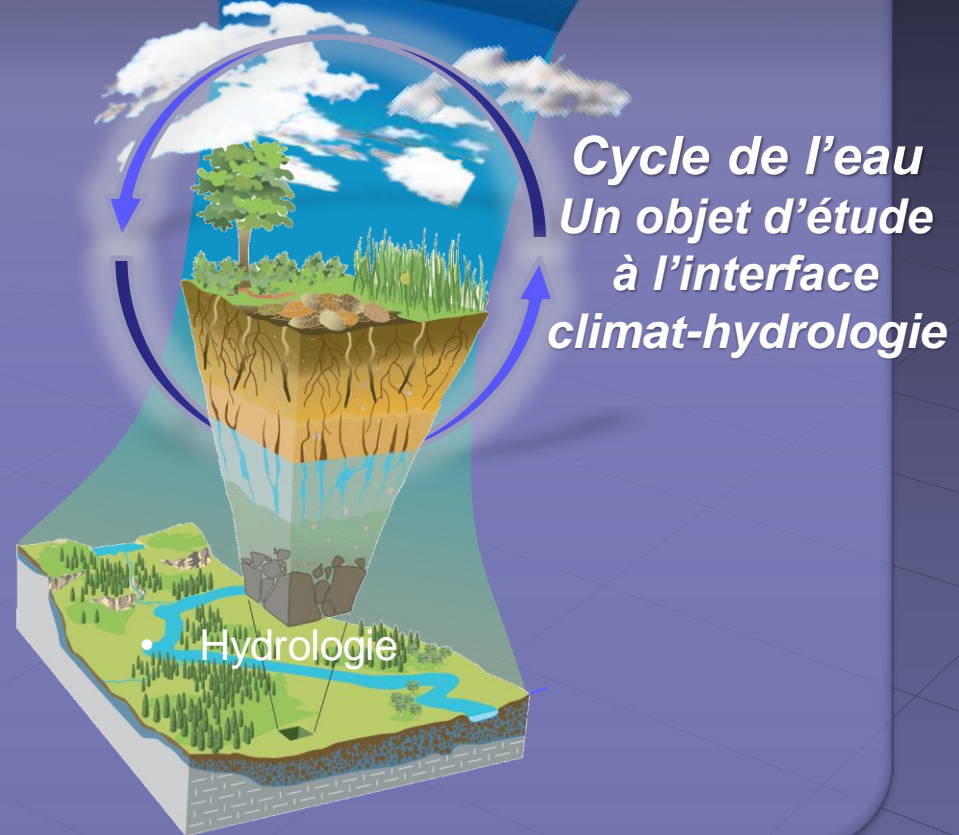


Terre externe



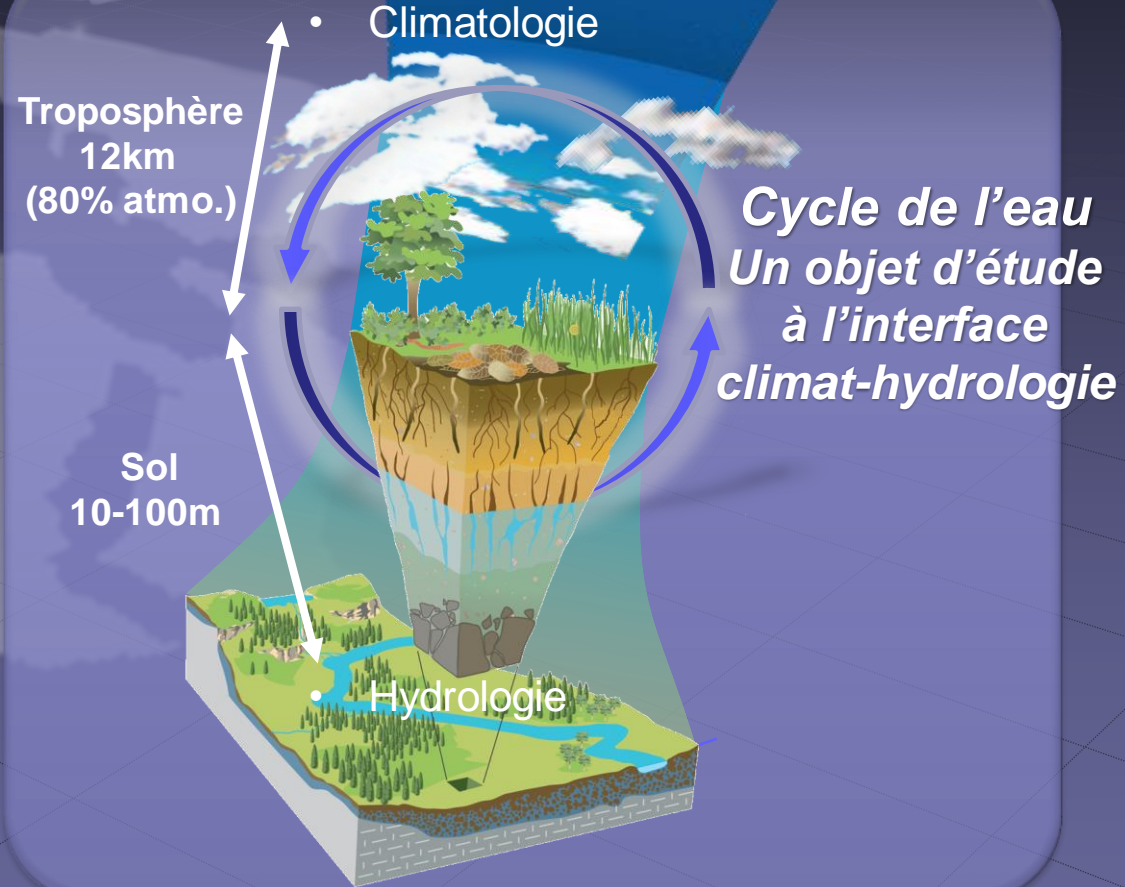
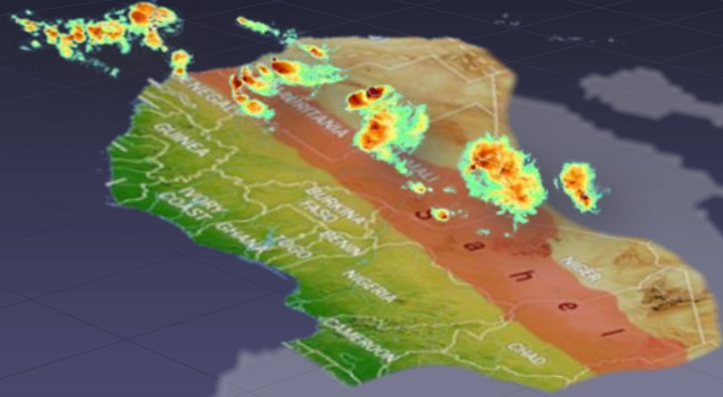
Mon domaine de recherche

- Climatologie

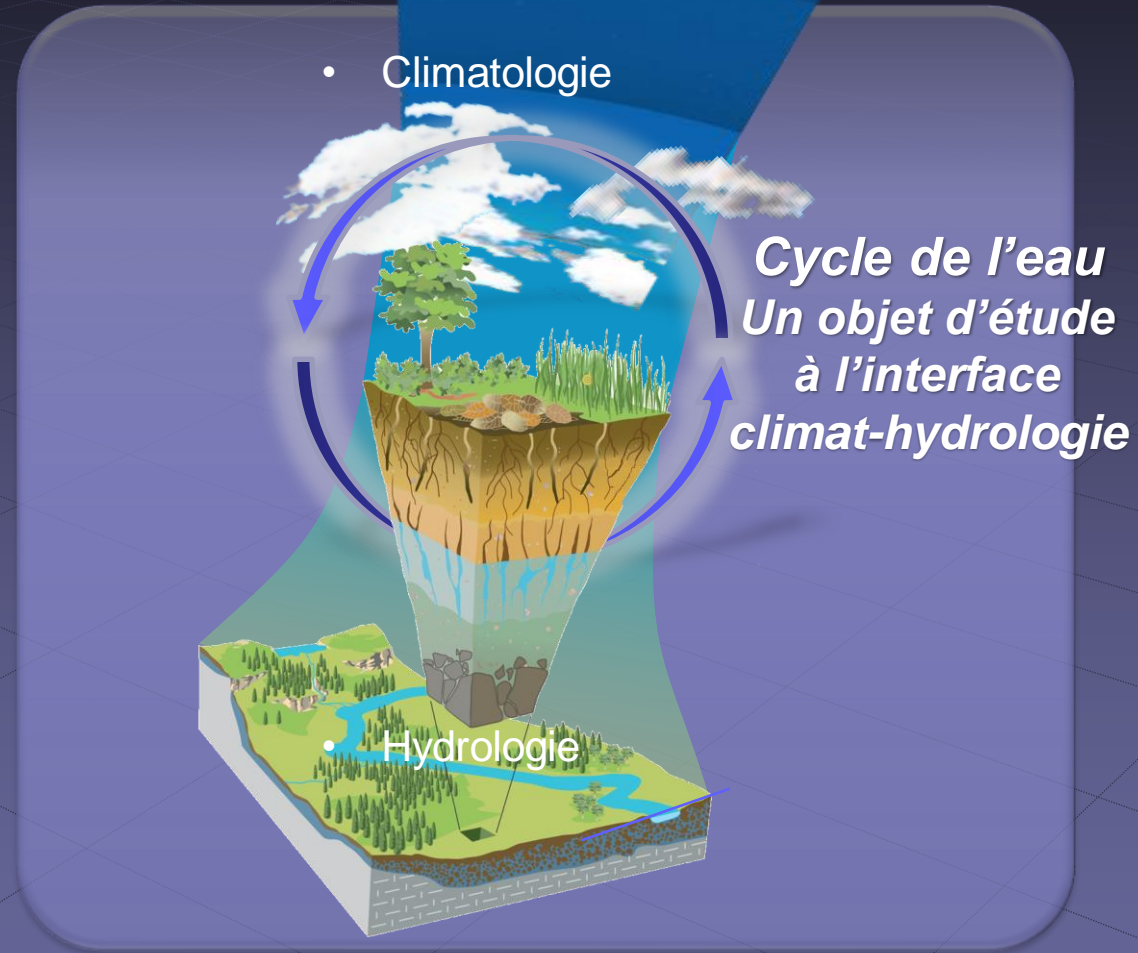


- Hydrologie

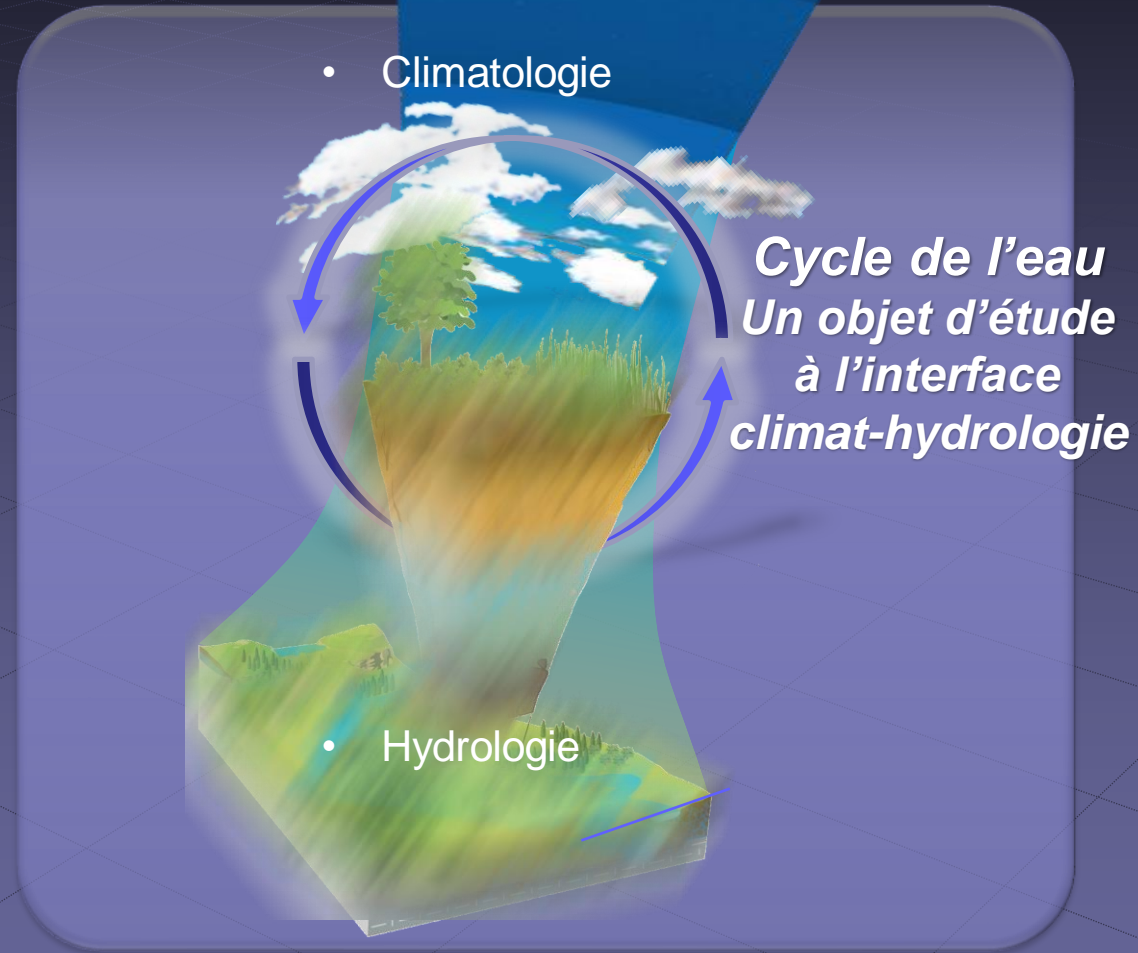
Mon domaine de recherche



Ma légitimité sur le sujet des limites planétaires

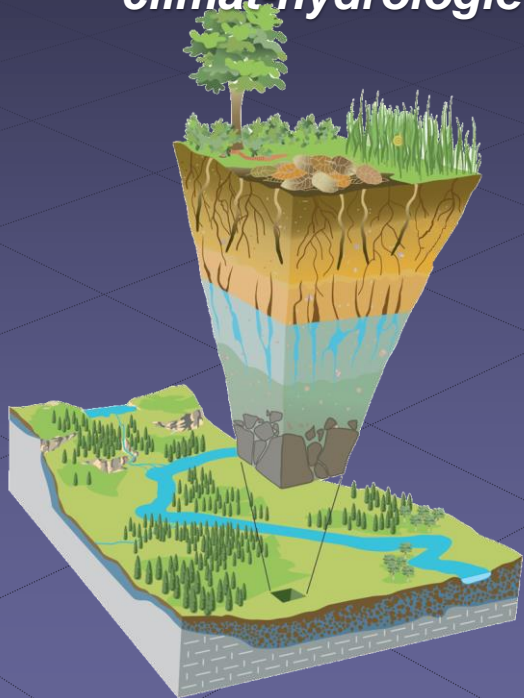


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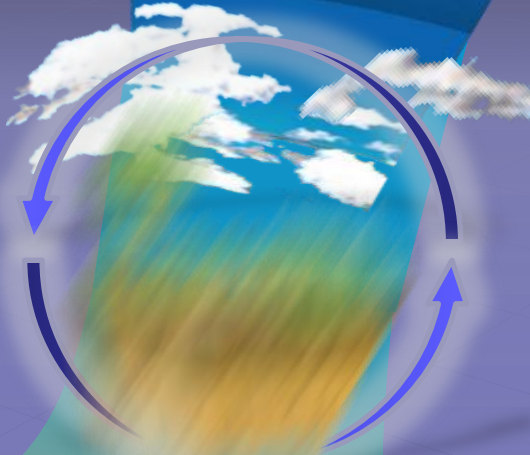
Ma légitimité sur le sujet des limites planétaires

Cycle de l'eau
Un objet d'étude
à l'interface
climat-hydrologie



Représentation dépassée
mais encore prégnante de
l'hydrologie

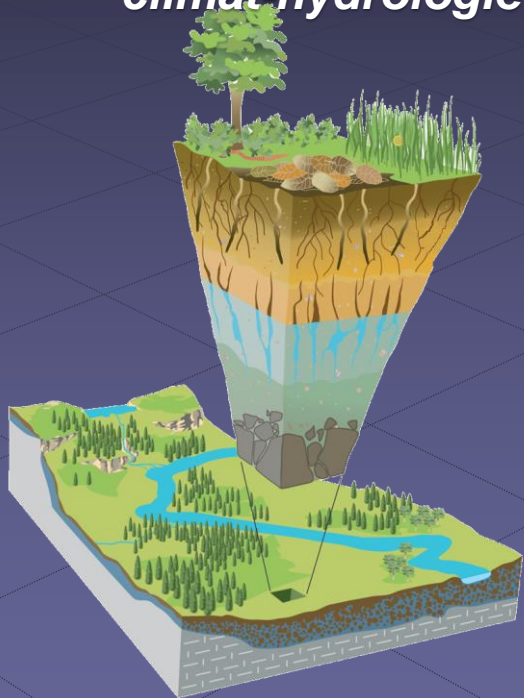
- Climatologie



- Hydrologie

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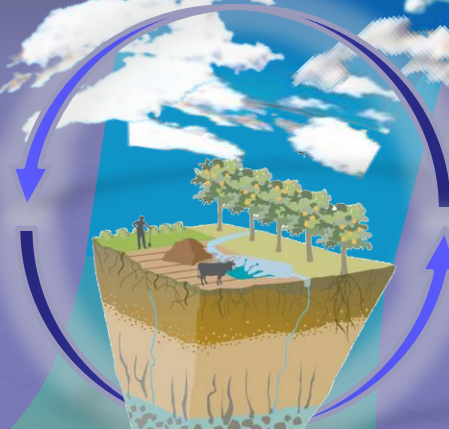


Représentation dépassée
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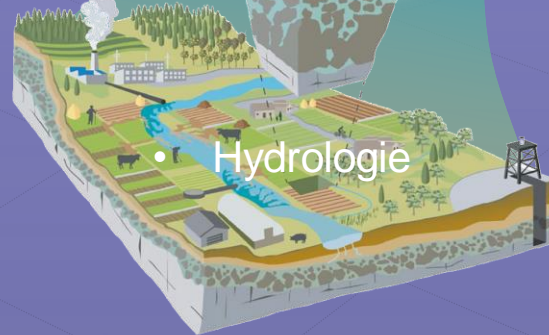
• Climatologie



Cycle de l'eau
Un objet d'étude
à l'interface
climat-hydrologie
Société



• Hydrologie



Ma légitimité sur le sujet des limites planétaires

Cycle de l'eau Une science de l'Anthropocène

nature
geoscience

ARTICLES

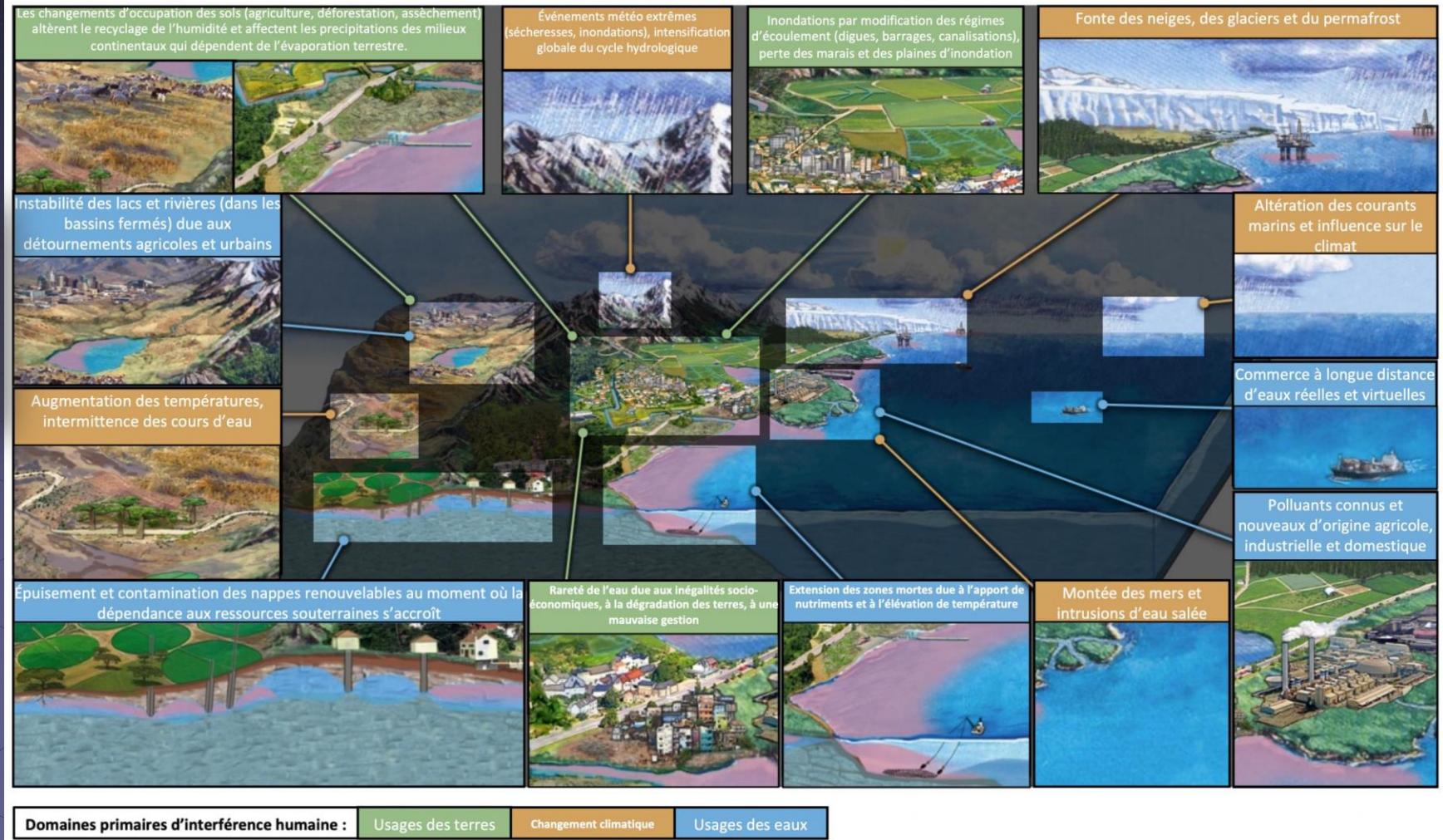
<https://doi.org/10.1038/s41561-019-0374-y>

Human domination of the global water cycle absent from depictions and perceptions

Benjamin W. Abbott^{1*}, Kevin Bishop², Jay P. Zarnetske³, Camille Minaudo^{4,5}, F. S. Chapin III⁶, Stefan Krause⁷, David M. Hannah⁸, Lafe Conner⁹, David Ellison¹⁰, Sarah E. Godsey¹¹, Stephen Plont^{12,13}, Jean Marçais¹⁴, Tamara Kolbe¹⁵, Amanda Huebner¹⁶, Rebecca J. Frei¹⁷, Tyler Hampton¹⁸, Sen Gu¹⁹, Madeline Buhman²⁰, Sayedah Sara Sayedi²¹, Ovidiu Ursache²², Melissa Chapin²³, Kathryn D. Henderson²⁴ and Gilles Pinay²⁵

Abott et al. 2019

c) Zoom sur quelques conséquences de l'interférence humaine sur le cycle de l'eau



Ma légitimité sur le sujet des limites planétaires

INITIATIVE INDIVIDUELLE

Mieux comprendre les interrelations entre hydrologie et société



UPPSALA
UNIVERSITET
CRCT 2023-24

INITIATIVES COLLECTIVES

Questionner mes pratiques de recherches

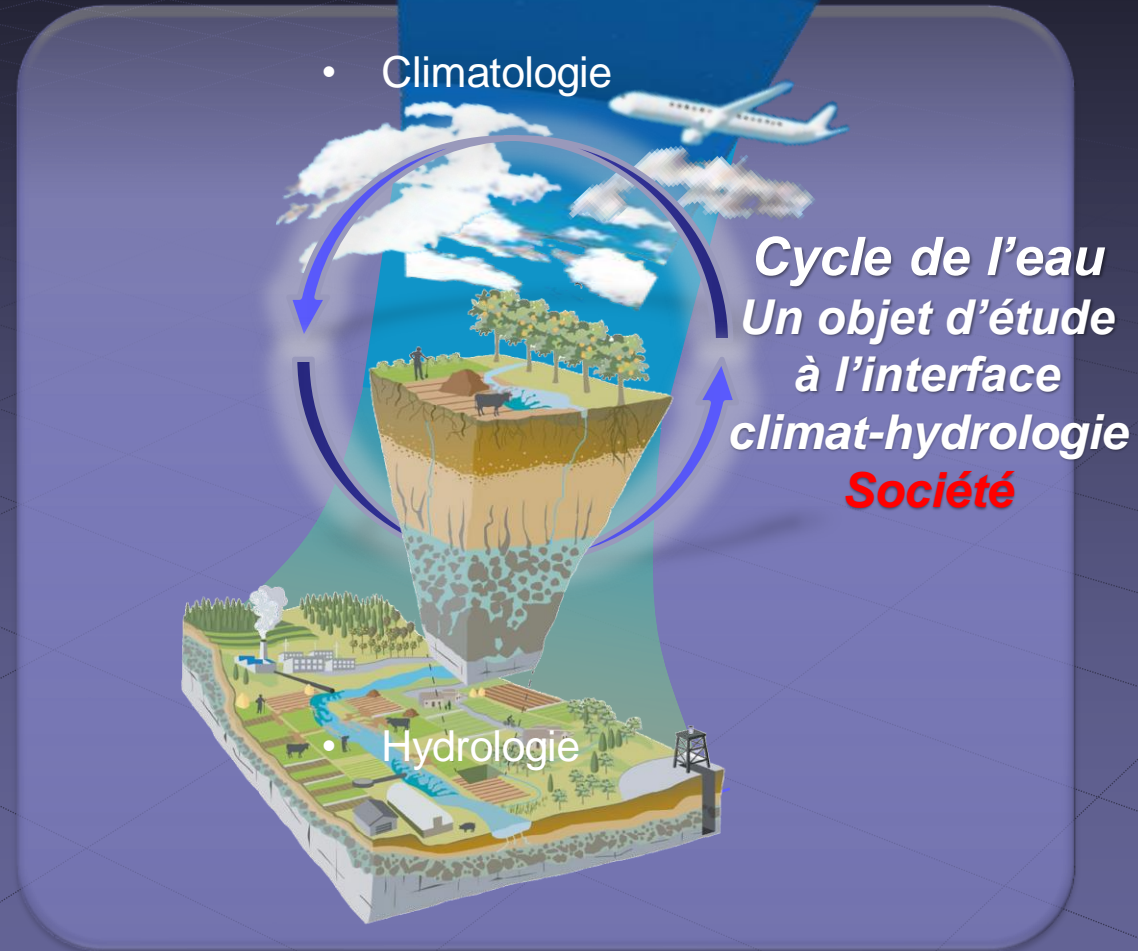


CAMPUS d'après Grenoble
Collectif de l'Anthropocène et de la Mobilisation Participative Universitaire et Sociale

Réorienter une partie de mes enseignements sur les enjeux socio-environnementaux



ANTHROPOCÈNE
ET LIMITES PLANÉTAIRES



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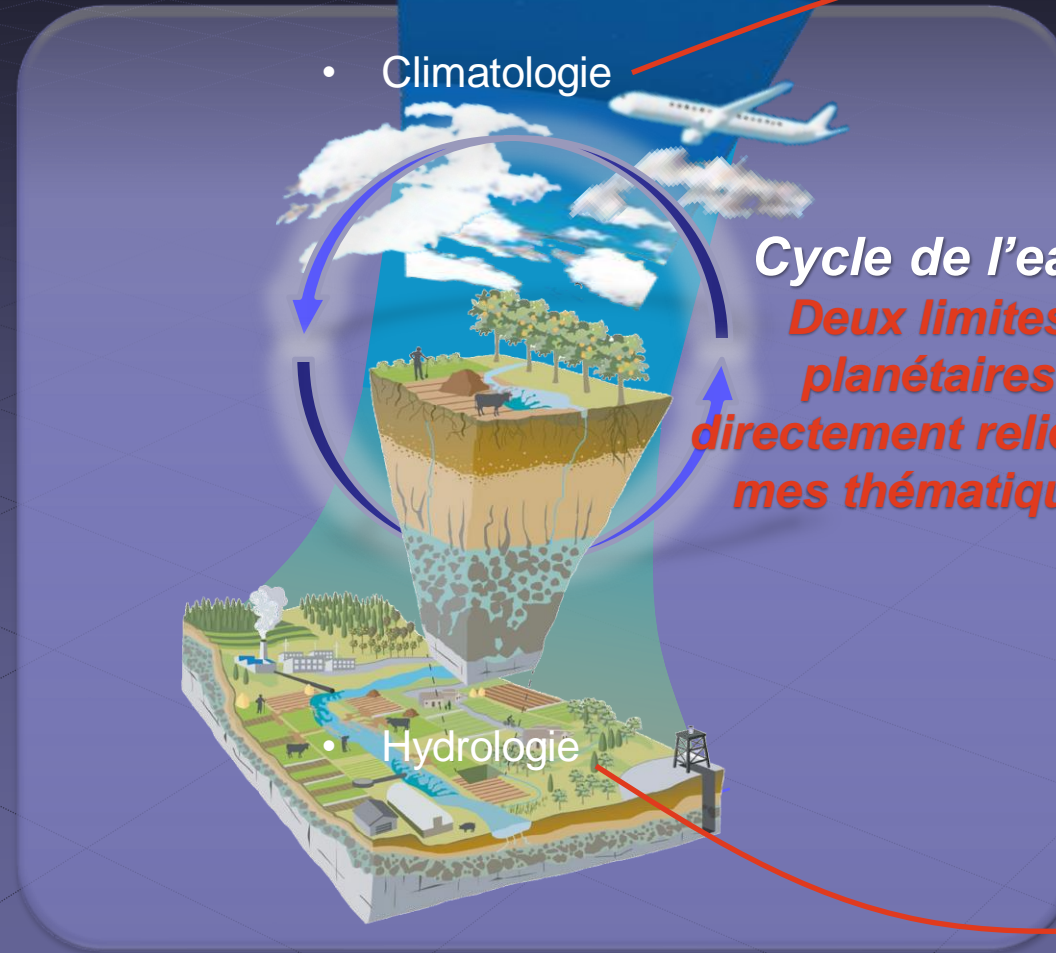


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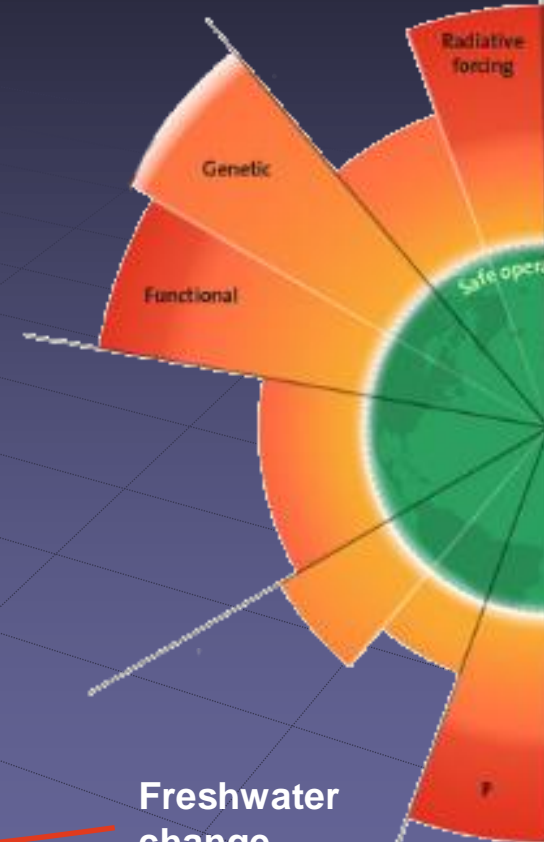
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ANTHROPOCÈNE
ET LIMITES PLANÉTAIRES



Climate change



Mes limites sur les limites

INITIATIVE INDIVIDUELLE

Mieux comprendre les interrelations entre hydrologie et société



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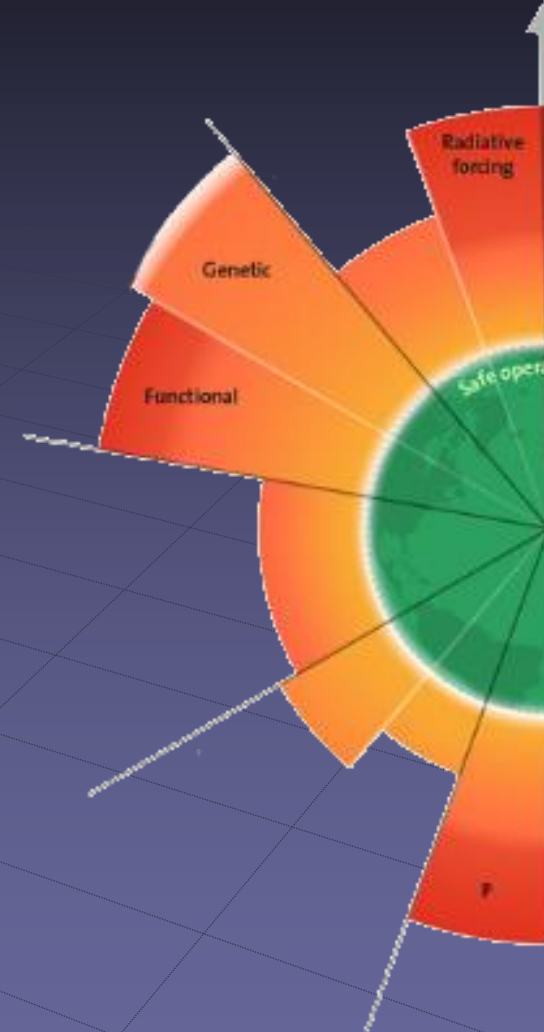
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ANTHROPOCÈNE
ET LIMITES PLANÉTAIRES

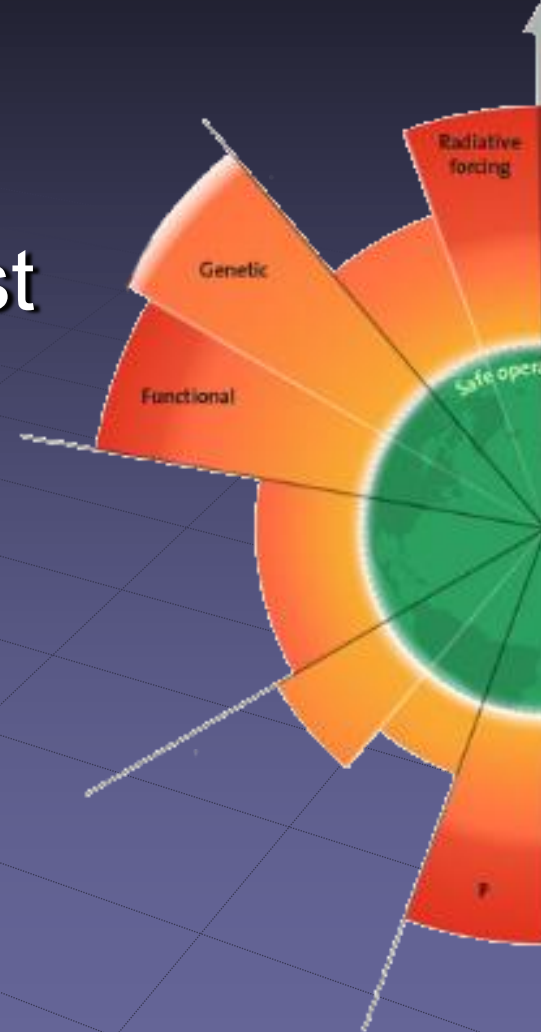


- Pas de publications personnelles sur le sujet
- Système terre: Objet pluri- inter- disciplinaire
 - Je ne suis pas omniscient
 - Je ne suis pas expert d'une grande partie des concepts mobilisés y compris dans mes thématiques scientifiques
- Lecture sur le sujet
 - Non exhaustive



Objectifs de la présentation

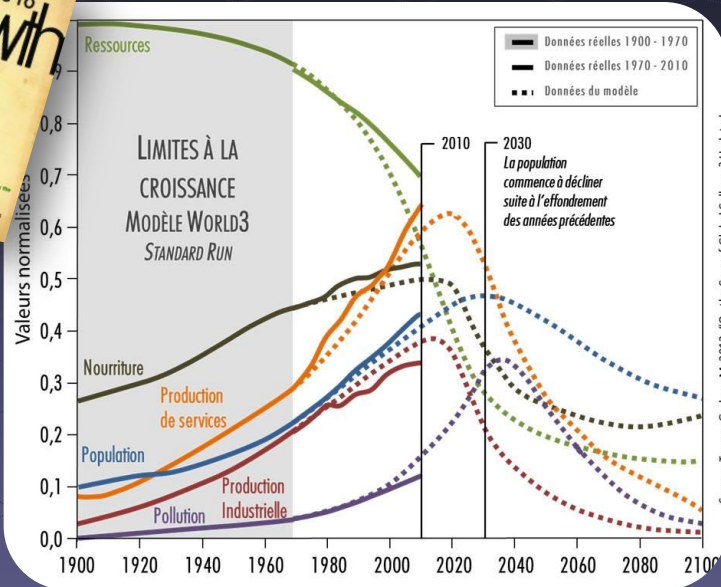
- Définir le concept
- Naviguer dans l'étendue littérature et montrer où est la science dans le concept et dans le débat qu'il suscite
- Ouvrir une discussion sur l'intérêt et les limites du concept et son utilisation



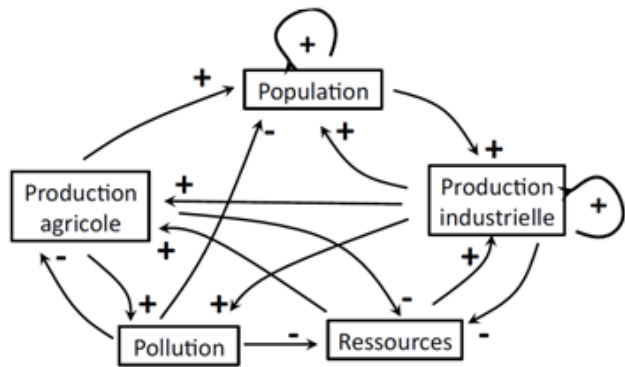
Définition des limites planétaires

Ce qu'elle ne sont pas...

Limites à la croissance



Comment la croissance économique et démographique peuvent conduire à un effondrement systémique sous contrainte des limites physiques des ressources naturelles et des pollutions engendrées.

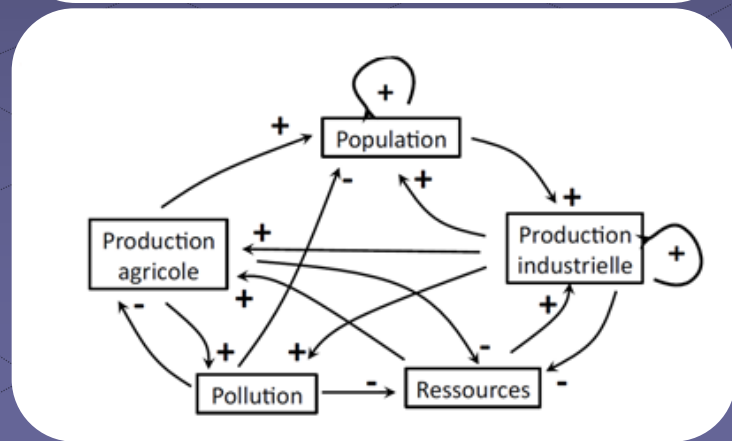
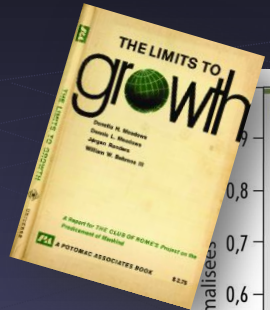
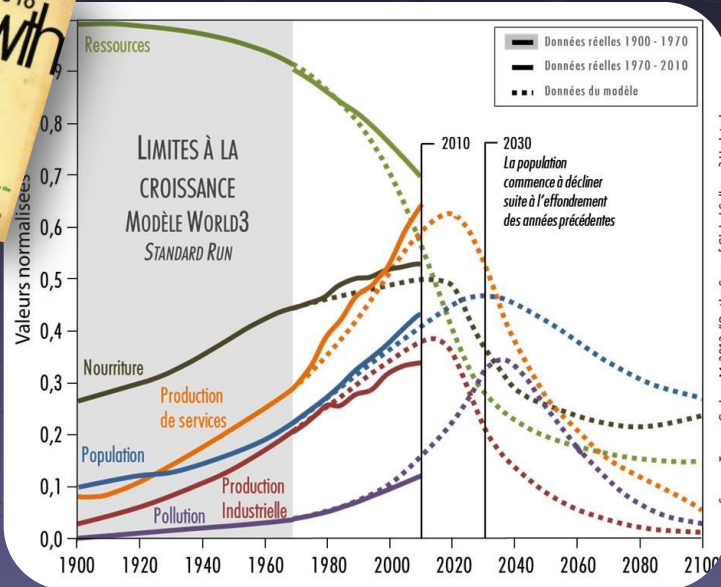


Meadows et al. 1972 (+ update)

Définition des limites planétaires

Ce qu'elle ne sont pas...

Limites à la croissance



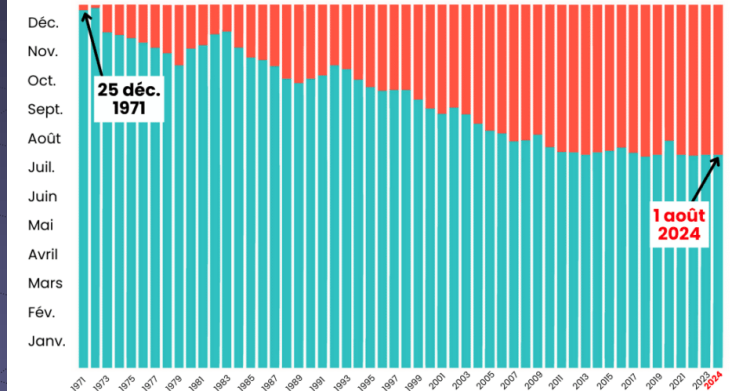
Meadows et al. 1972 (+ update)

- Comparaison entre:
- Empreinte: Superficie des terres et des océans pour produire la ressource consommée et absorber les déchets générés
 - Biocapacité: la superficie des terres et des océans effectivement disponible pour régénérer les ressources et absorber les pollutions.

Empreinte écologique

Ce jeudi 1^{er} août 2024, c'est le jour du dépassement de la Terre

Evolution du jour du dépassement de la Terre : 1971-2024



Nombre de planètes Terre "consommées"



1 planète Terre en 1971

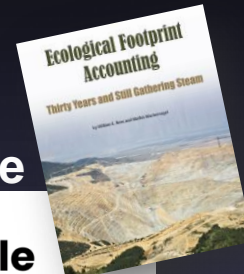


1,75 planète Terre en 2024

Source: National Footprint and Biocapacity Accounts, édition 2024
data.footprintnetwork.org

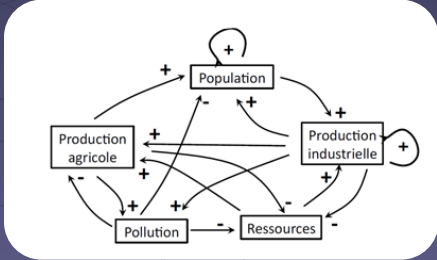
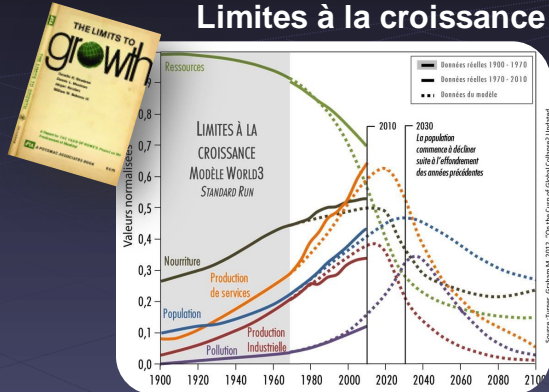


Rees, 1992, Wackernagel and Rees, 1996



Définition des limites planétaires

Ce qu'elle ne sont pas...



Meadows et al. 1972 (+ update)

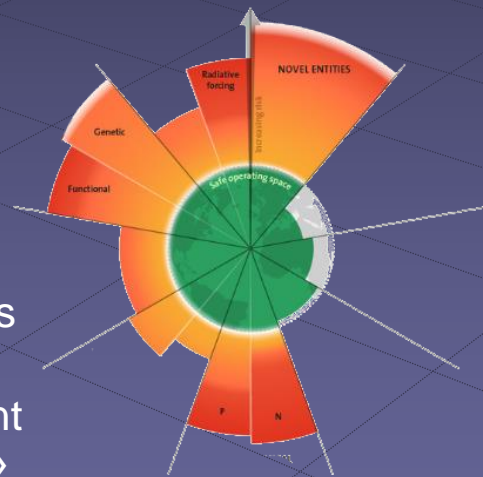
Facteurs socio-économiques

Ressources/Pollutions

Filiation revendiquée
(Rockström et al. 2009a)

Définir des seuils critiques indépendants des choix socio-économiques et dont le caractère « physique » est non-négociable

Limites Planétaires



Système Terre

Indicateurs Globaux

Donner une voix à la Terre dans les instances de négociations à partir d'indicateurs globaux

Empreinte écologique

Ce jeudi 1^{er} août 2024, c'est le jour du dépassement de la Terre

Evolution du jour du dépassement de la Terre : 1971-2024

25 déc. 1971

1 août 2024

Nombre de planètes Terre « consommées »

1 planète Terre en 1971

1,75 planète Terre en 2024

Source: National Footprint and Biocapacity Accounts, édition 2024
data.footprintnetwork.org

vert

Rees, 1992, Wackernagel and Rees, 1996

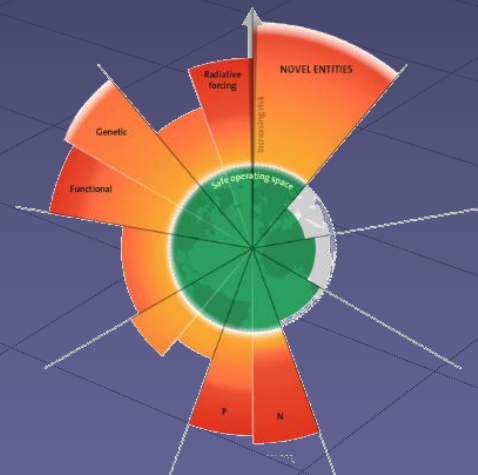
Définition des limites planétaires

« The planetary boundaries framework defines a safe operating space for humanity based on the intrinsic biophysical processes that regulate the stability of the Earth system. »

(Rockström et al. 2009a,b; Steffen et al. 2015; Richardson et al. 2023)

Le cadre des limites planétaires définit un espace de fonctionnement sûr pour l'humanité sur la base des processus biophysiques intrinsèques qui régulent la stabilité du système terre.

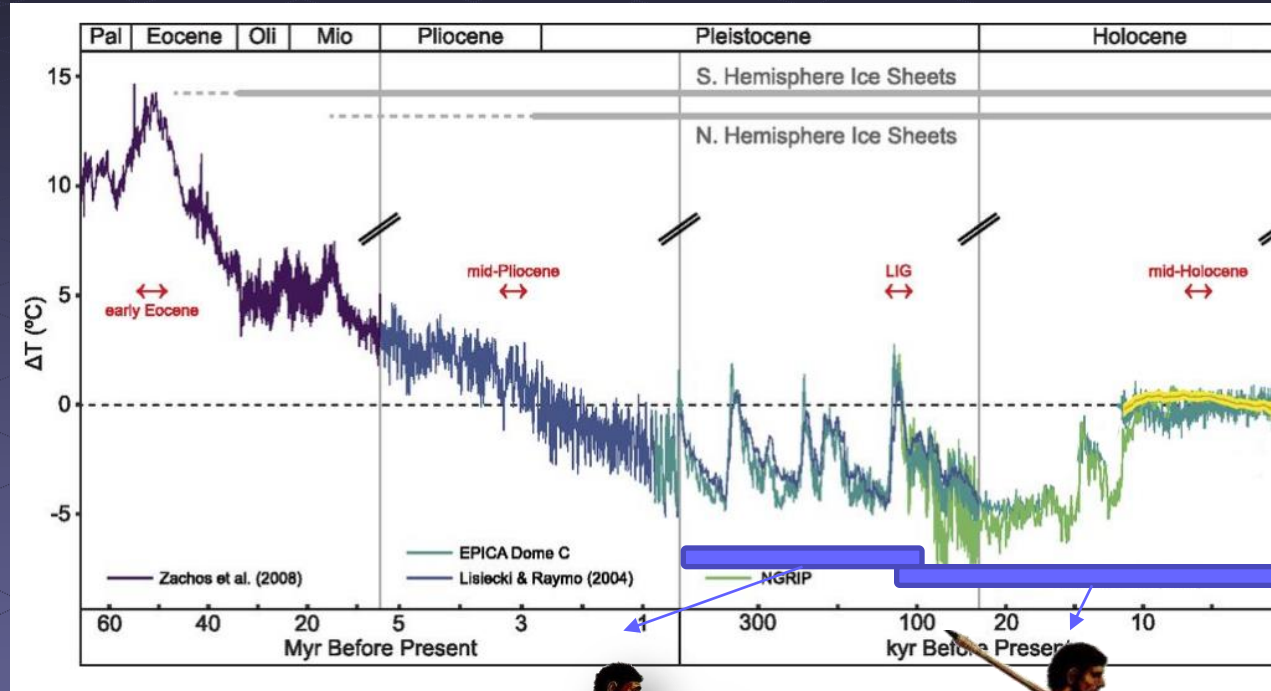
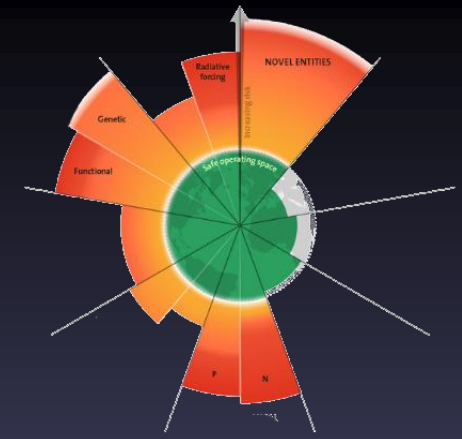
Limites Planétaires



Systeme Terre

Définition des limites planétaires

« The planetary boundaries framework defines a safe operating space for humanity based on the intrinsic biophysical processes that regulate the **stability of the Earth system**. »
(Rockström et al. 2009a,b; Steffen et al. 2015; Richardson et al. 2023)



Homo Erectus

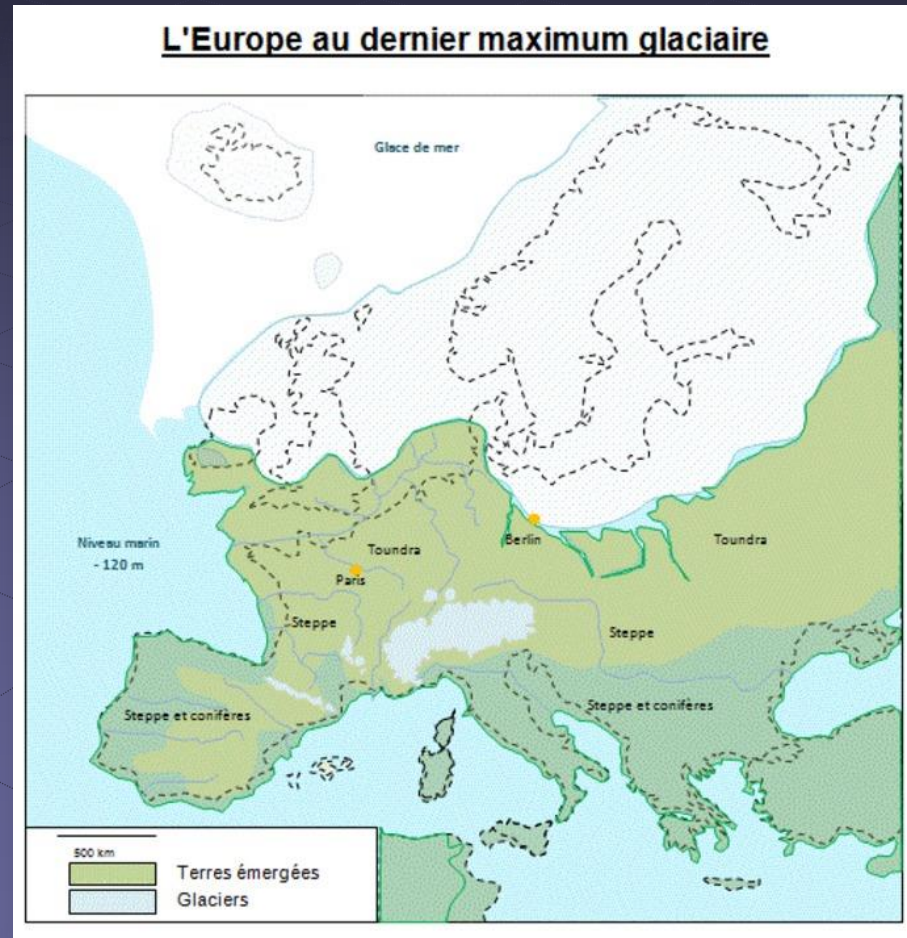
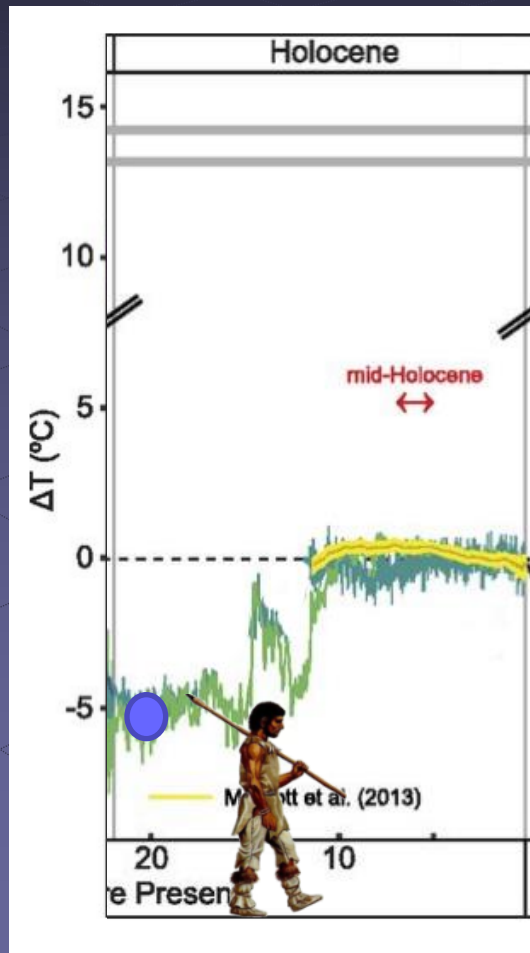


Homo Sapiens

Définition des limites planétaires

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(Rockström et al. 2009a,b; Steffen et al. 2015; Richardson et al. 2023)

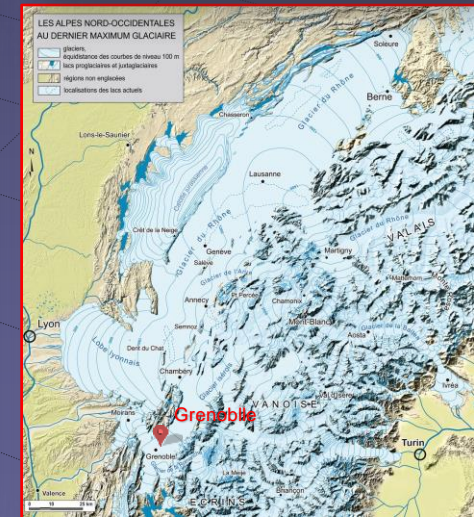
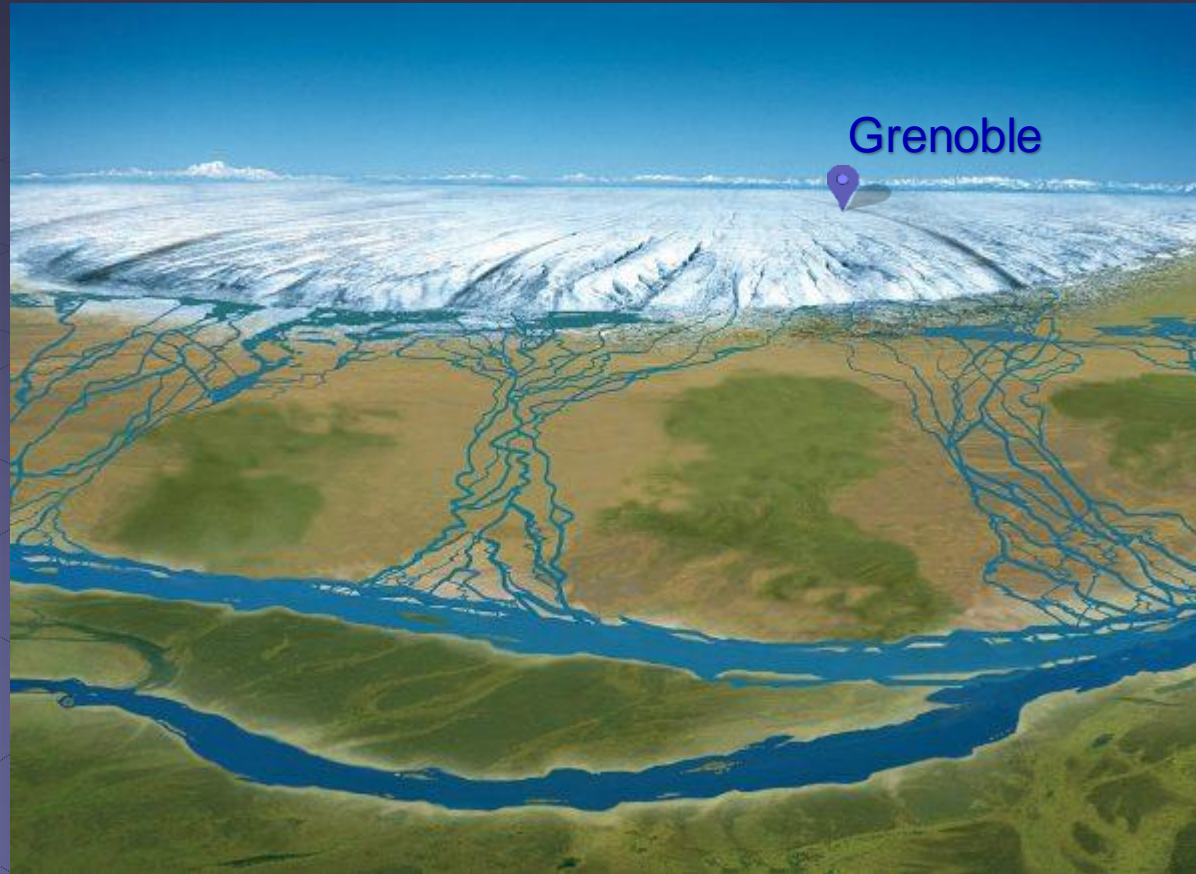
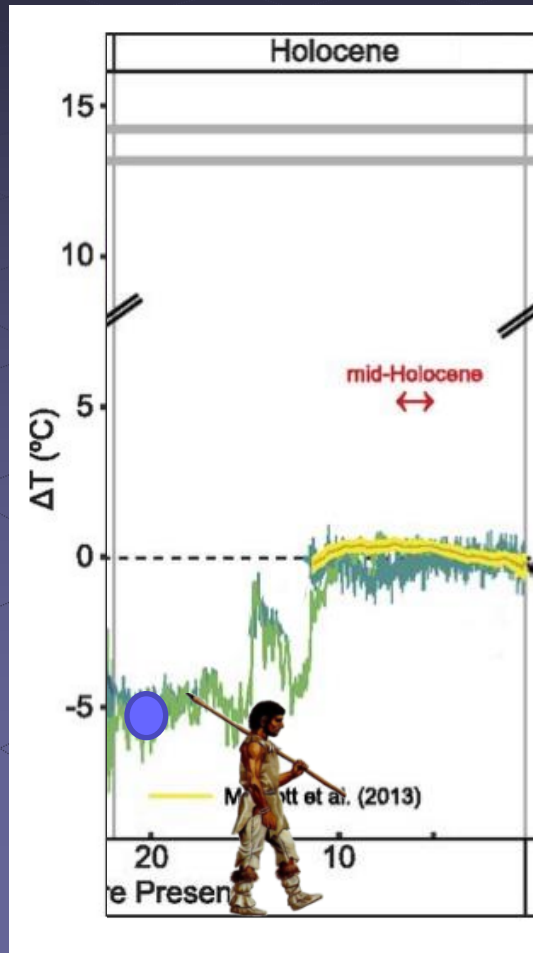


La température de la planète était plus froide qu'aujourd'hui de 5°C

Définition des limites planétaires

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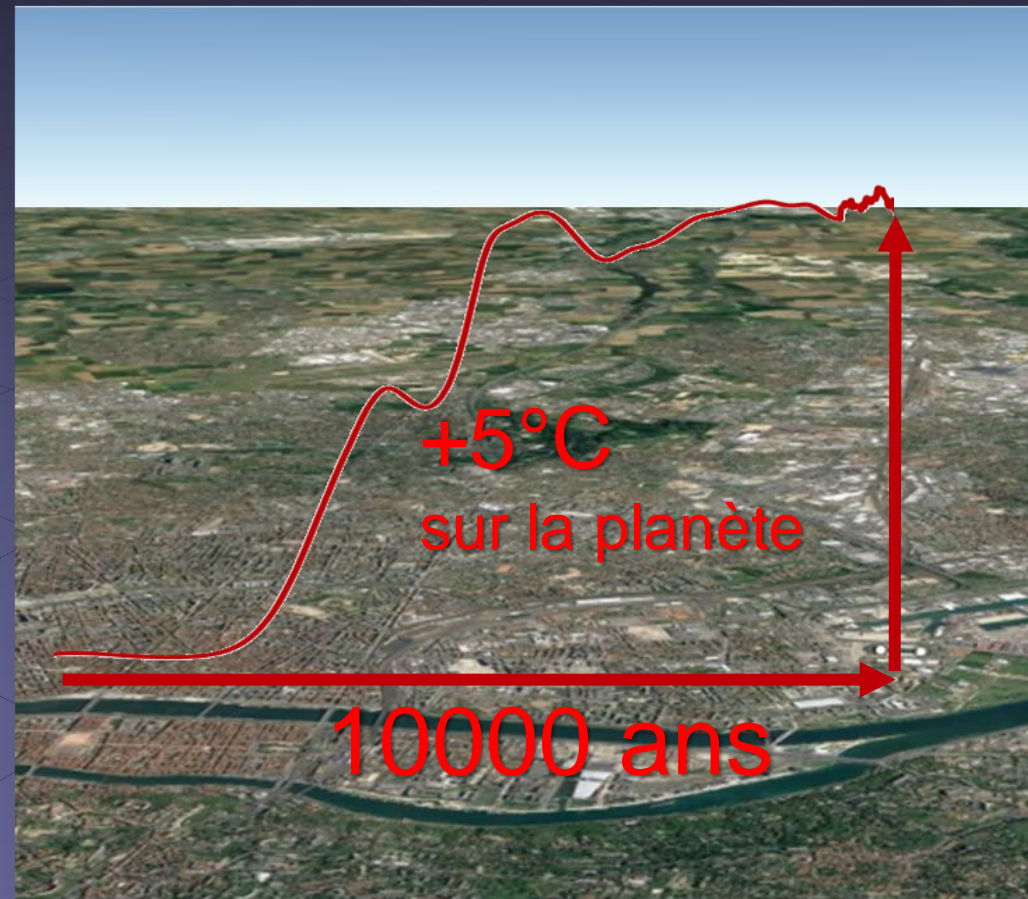
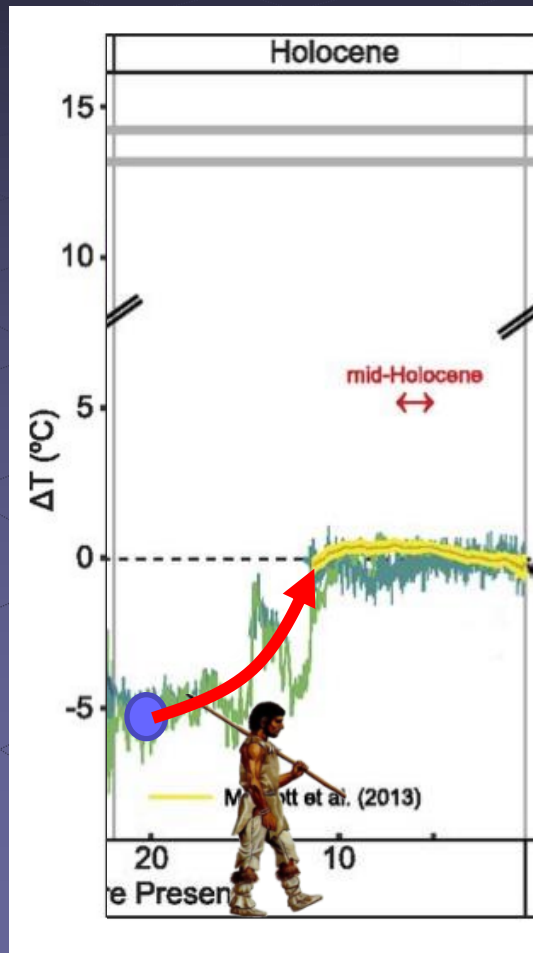
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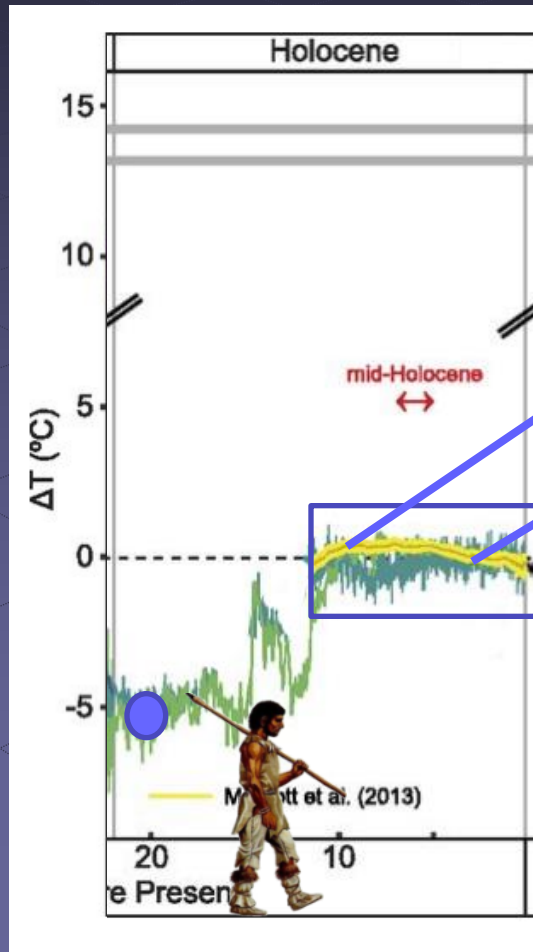
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(Rockström et al. 2009a,b; Steffen et al. 2015; Richardson et al. 2023)



- Début de l'agriculture
- Développement des grandes civilisations sur l'ensemble des continents.
- Des impacts humains connus (modifications d'occupation des sols, des feux, extinction d'espèces) mais rien de global jusqu'ici.

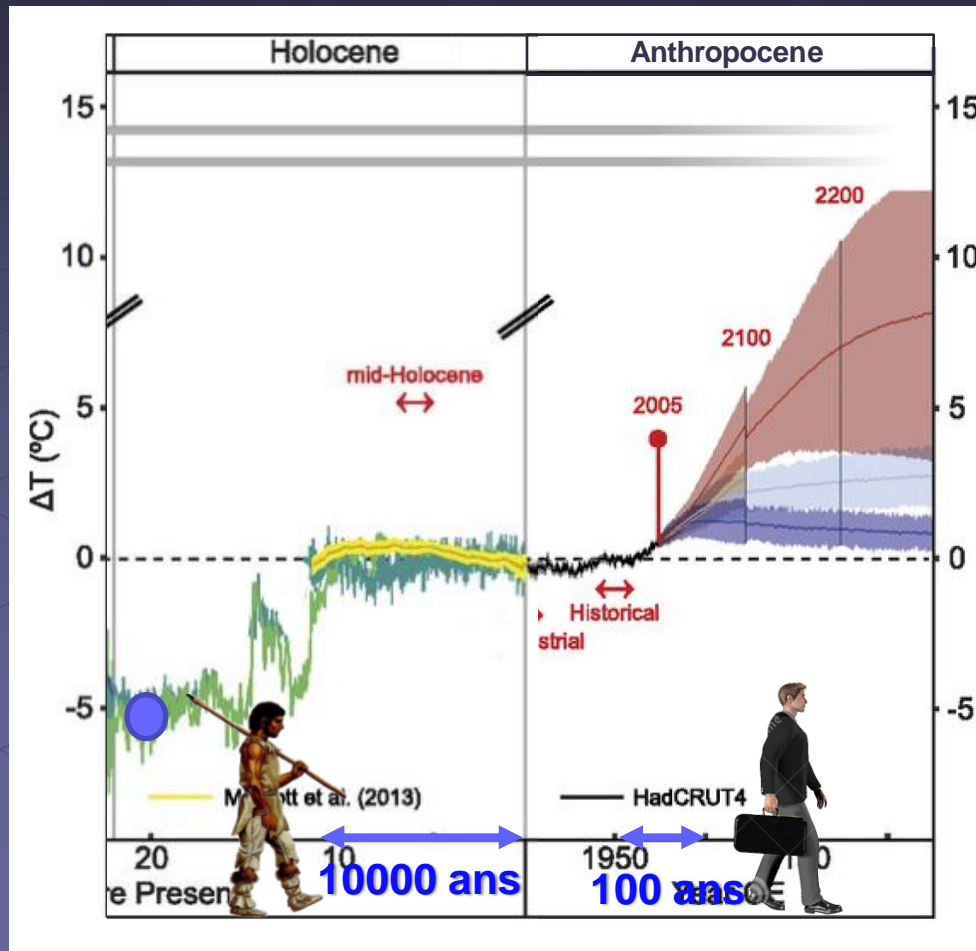
« The relatively stable, 11,700-year-long Holocene epoch, [is] the only state of the planet that we know for certain can support contemporary human societies »

Steffen et al. 2015

Définition des limites planétaires

« The planetary boundaries framework defines a safe operating space for humanity based on the intrinsic biophysical processes that regulate the **stability of the Earth system**. »

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**Anthropogenic
Climate
Change**

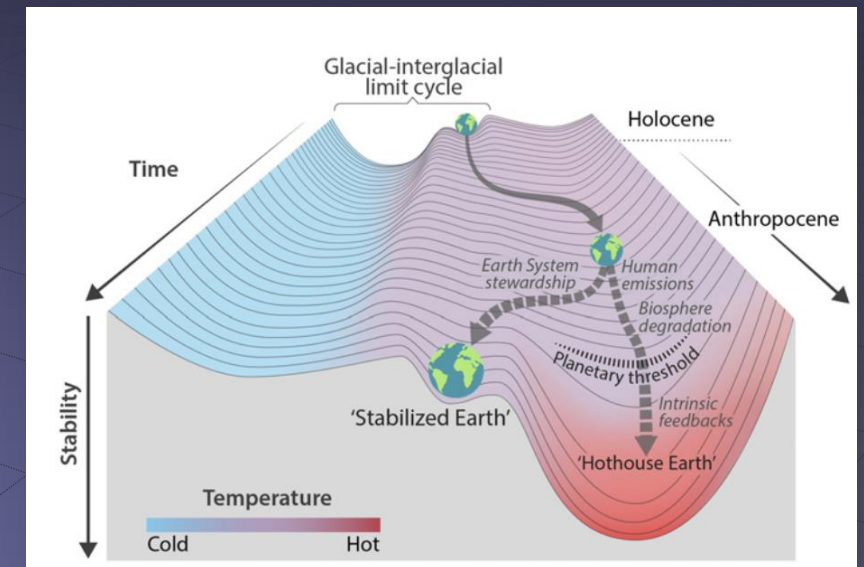
+1.3°C

en 100 ans!

+1.5° +3° +6°C

en 200 ans?

Evolution future qui pose la question de la réversibilité des trajectoires



Steffen et al. 2018, PNAS

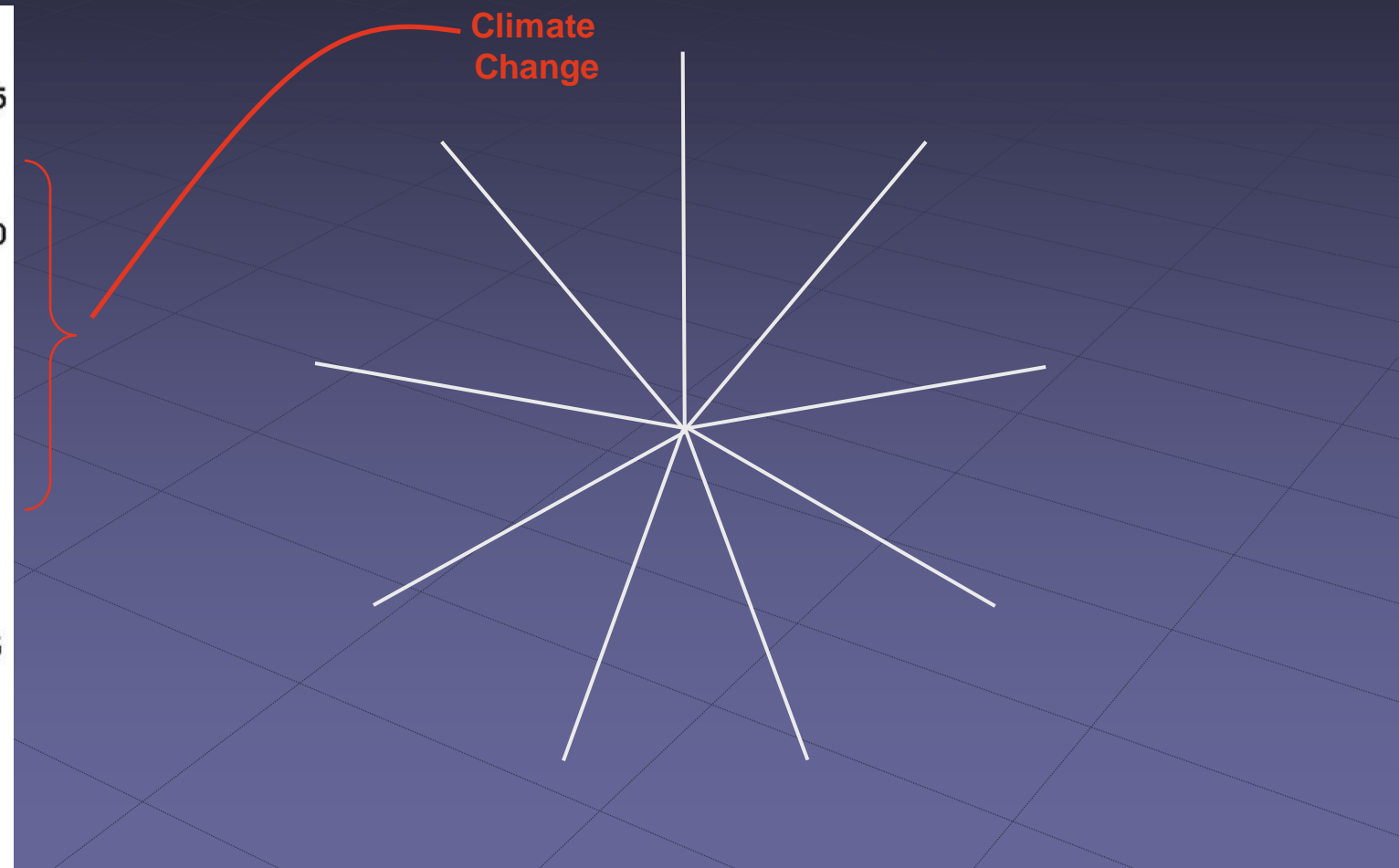
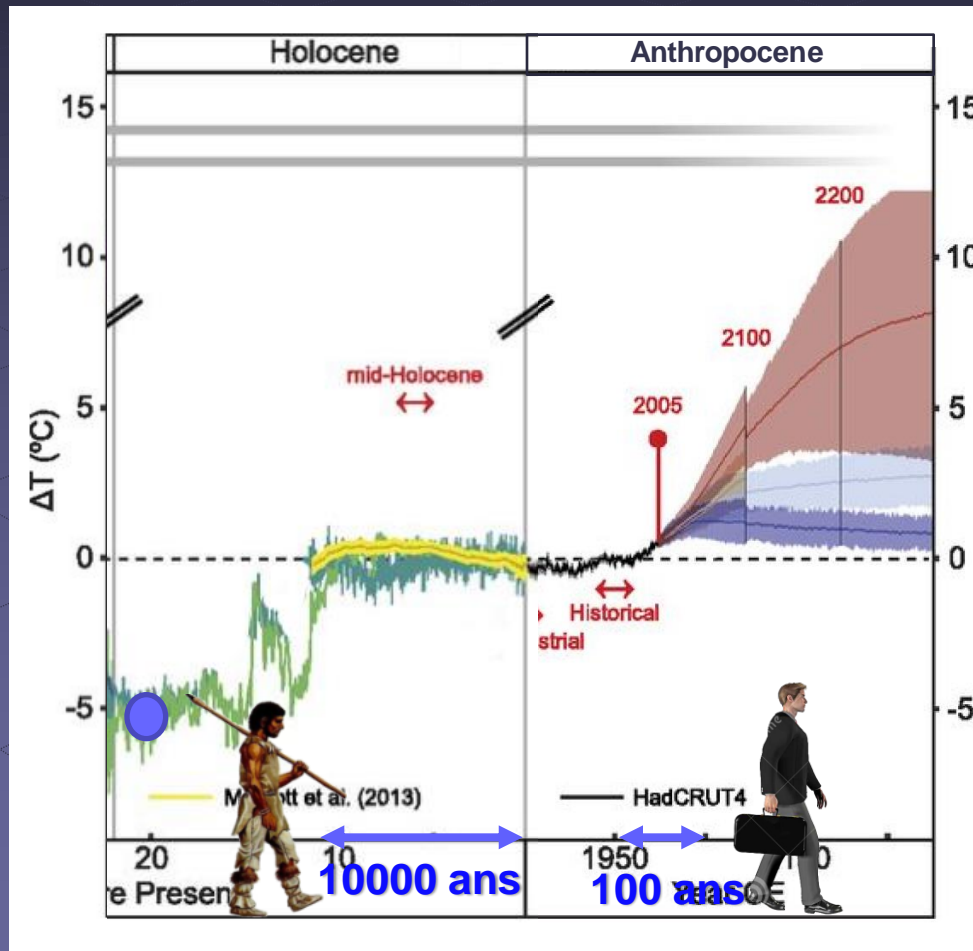
“Environmental changes that would be deleterious or even catastrophic for human well-being”

Rockström et al. 2009a

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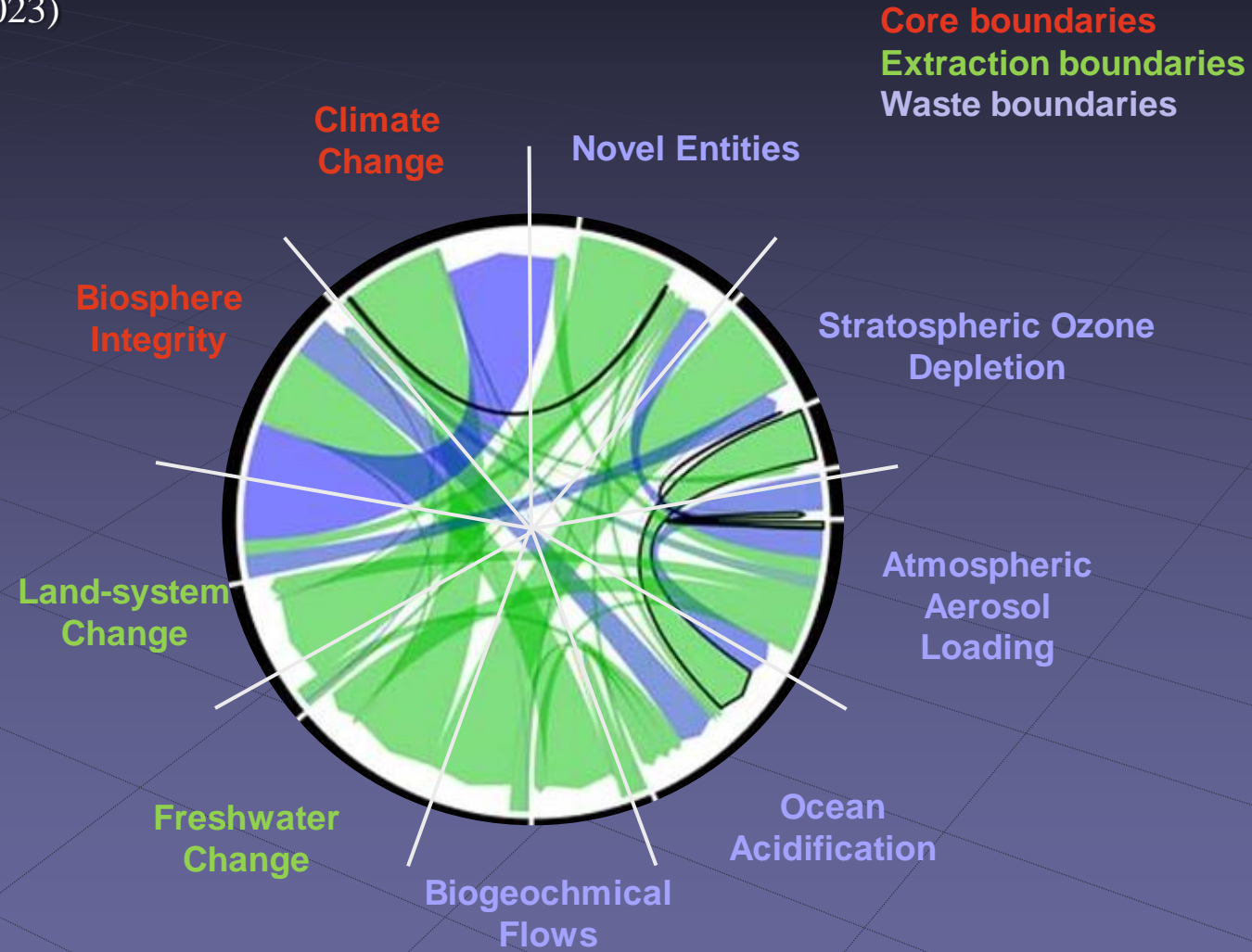
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Cadre d'analyse

- **9 processus biophysiques**
 - Déterminent la capacité d'auto-régulation du système Terre



Lade et al. 2020

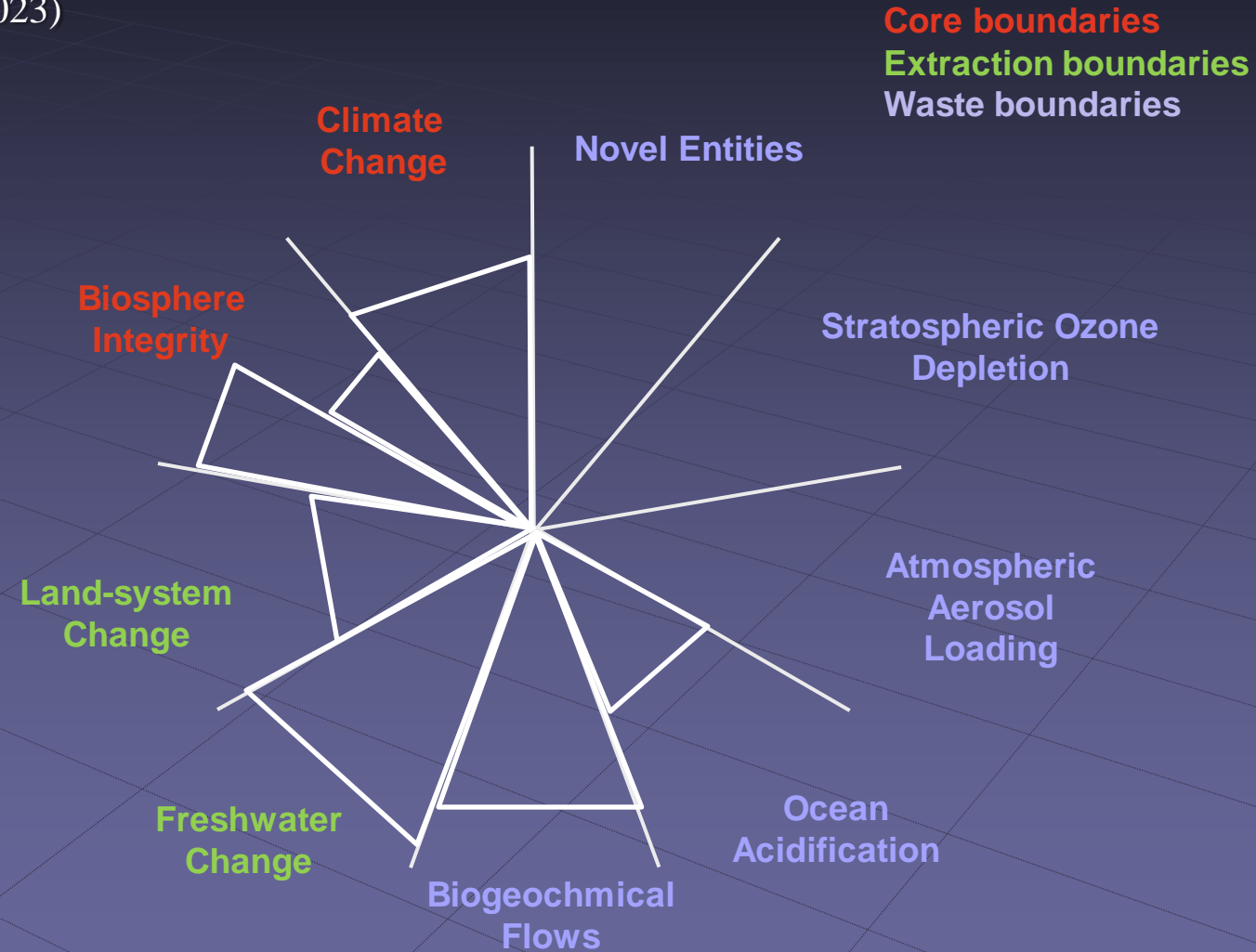
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 - Descripteurs (1 ou 2) de chaque processus
 - Echelle globale – ou régionale agrégée



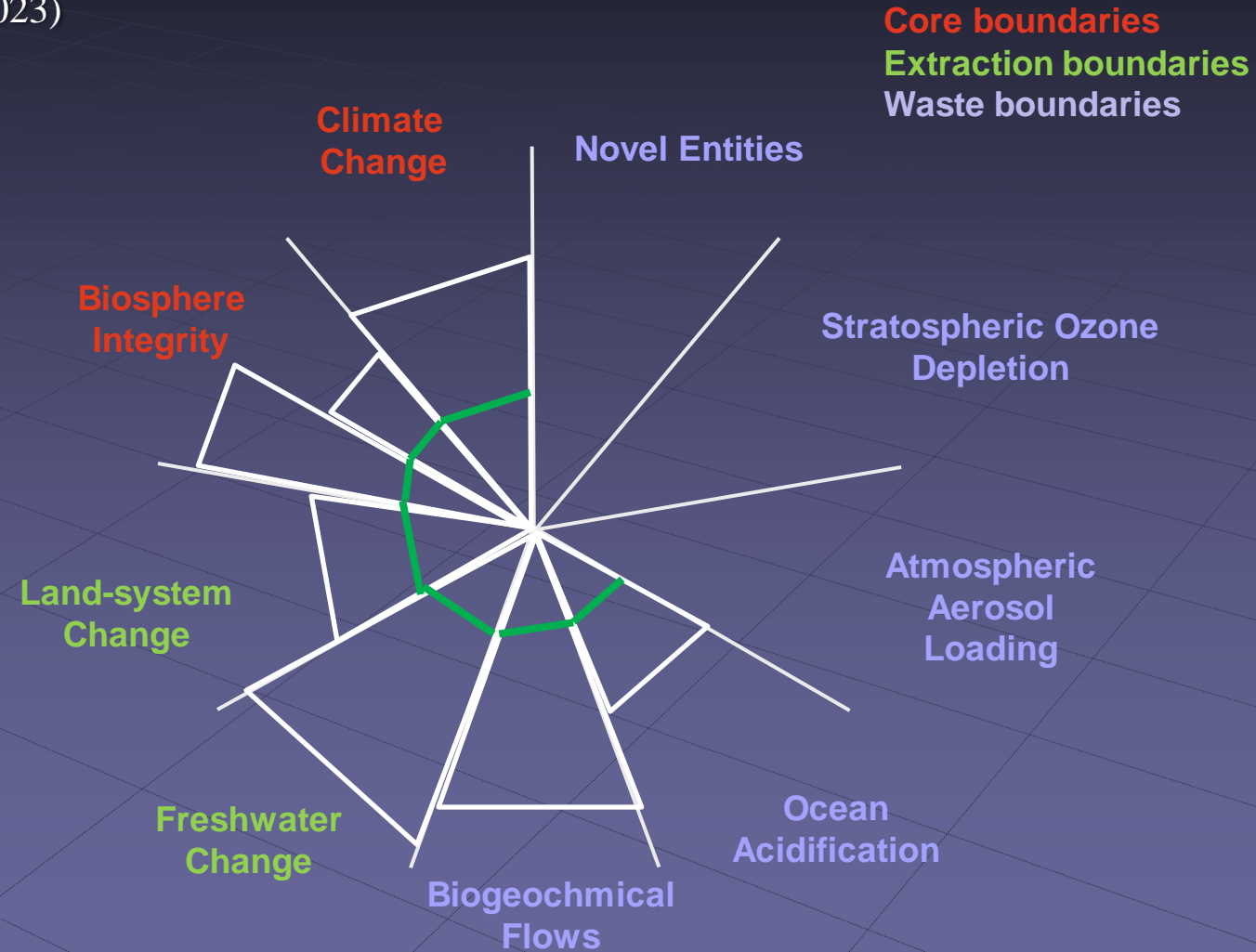
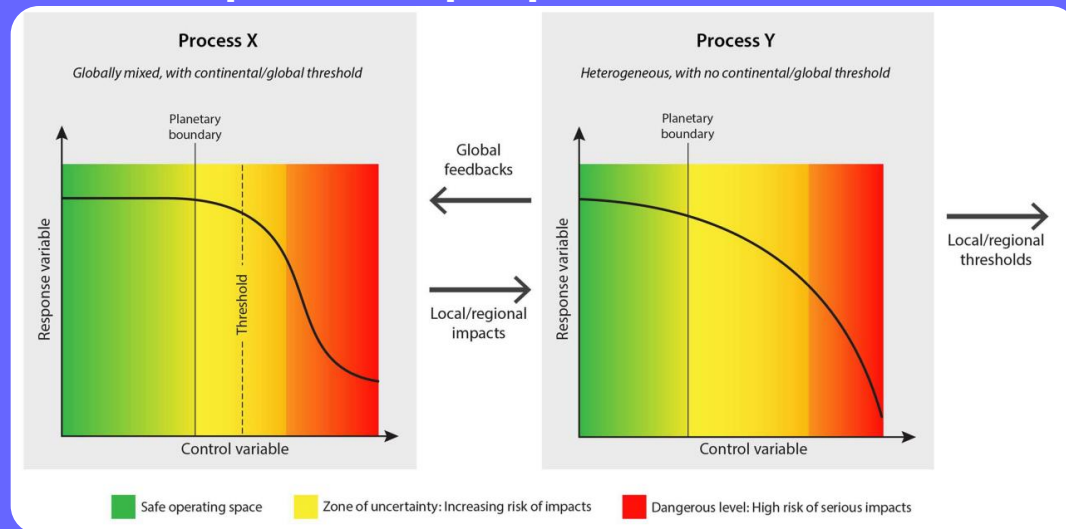
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 - Echelle globale – ou régionale agrégée
- **Seuils pour chaque processus**



Définition des limites planétaires

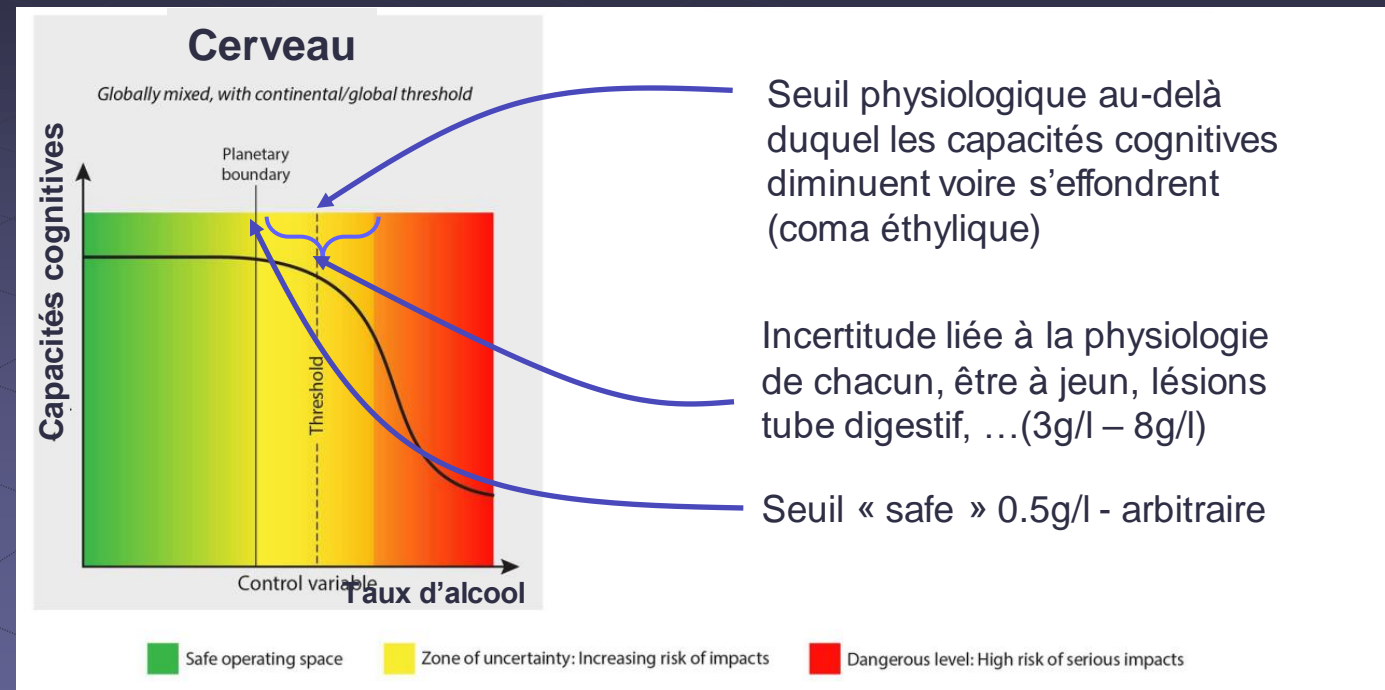
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(Rockström et al. 2009a,b; Steffen et al. 2015; Richardson et al. 2023)

Traduction personnelle

Le cadre des limites planétaire permet d'évaluer si la Terre est en bonne santé:

- les processus sont les organes vitaux de la Terre
- les seuils sont les valeurs critiques
- les limites sur l'organe sont les valeurs à ne pas franchir pour ne pas menacer le fonctionnement d'un organe



Variable à seuil

Définition des limites planétaires

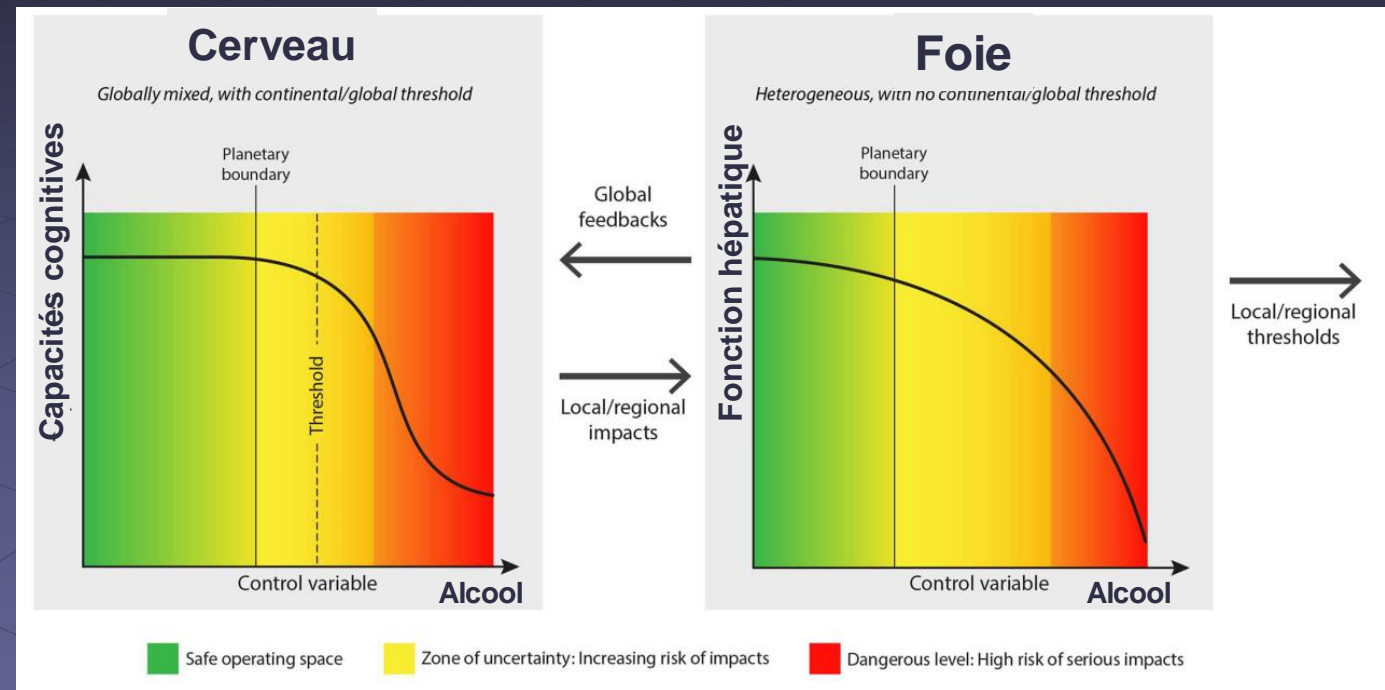
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- les limites sur l'organe sont les valeurs à ne pas franchir pour ne pas menacer le fonctionnement d'un organe
- ou avoir un impact important sur un autre organe
- l'Holocène définit l'état de bonne santé de référence.



Variable à seuil

Seuil non défini

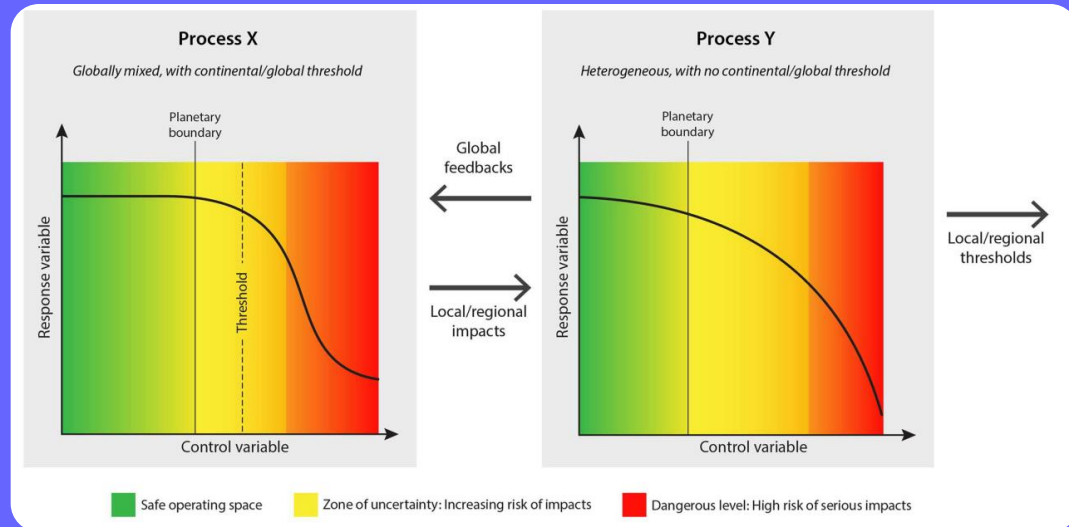
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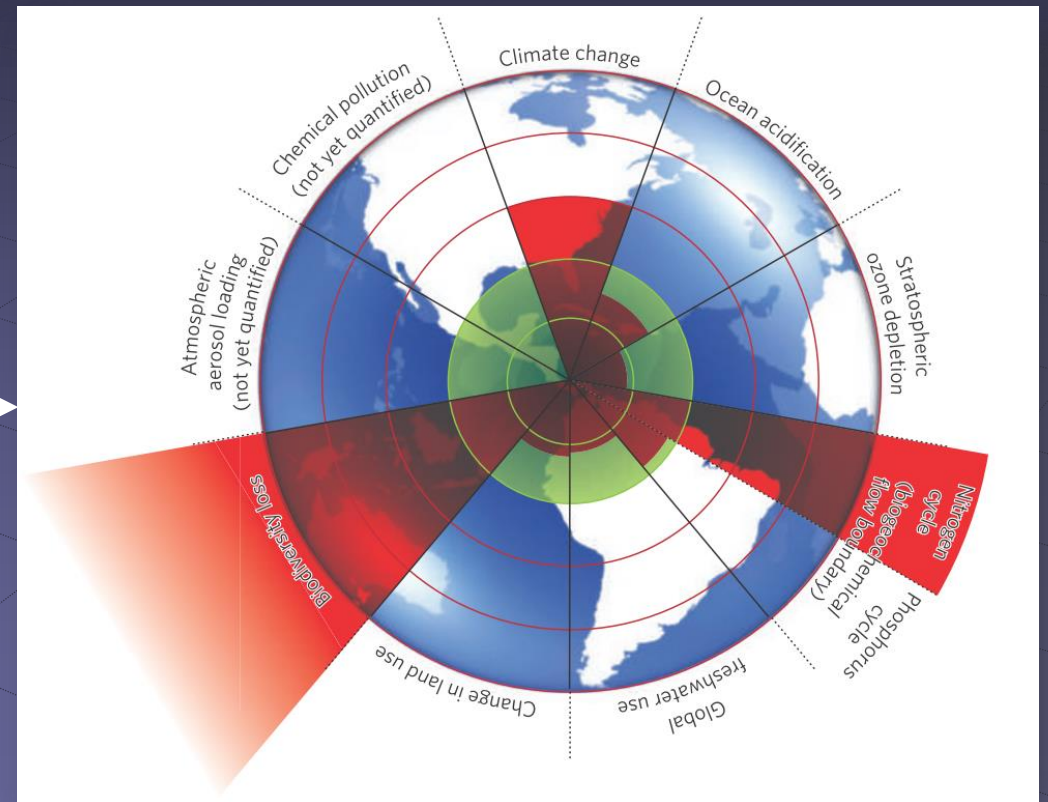
(Rockström et al. 2009a,b; Steffen et al. 2015; Richardson et al. 2023)

Cadre d'analyse

- **9 processus biophysiques**
 - Déterminent la capacité d'auto-régulation du système Terre
- **Variables de contrôle**
 - Descripteurs (1 ou 2) de chaque processus
 - Echelle globale – ou régionale agrégée
- **Seuils pour chaque processus**



Quelle science derrière le concept ?



Rockström et al. 2009b, Nature

Quelle science derrière le concept ?

Rockström et al. 2009b, Nature
!! Non peer-reviewed !!

FEATURE
A safe operating space for humanity
Identifying and quantifying planetary boundaries that must not be transgressed could help prevent human activities from causing unacceptable environmental change, argue Johan Rockström and colleagues.

SUMMARY
• New approach proposed for defining preconditions for human development
• Crossing certain biophysical thresholds could have disastrous consequences for humanity
• Three of nine interrelated planetary boundaries have already been overstressed

Planetary boundaries
To meet the challenge of maintaining the Holocene state, we propose a framework based on 'planetary boundaries'. These boundaries define the safe operating space for humanity with respect to the Earth system and are associated with the planet's biophysical subsystems or processes. Although Earth's complex systems sometimes respond nonlinearly to changing pressures, it seems that this will prove to be the exception rather than the rule. Many subsystems of Earth react in a nonlinear, often abrupt, way and periodically sensitive around threshold levels of certain key variables. If these thresholds are crossed, then important subsystems, such as a common system, could shift into a new state, often with deleterious or potentially even disastrous consequences for humanity.

Figure 1 Beyond the boundary. The inner grey shading represents the proposed safe operating space for nine planetary systems. The red wedges represent an estimate of the current position for each variable. The boundaries in these systems (rate of biodiversity loss, climate change and human interference with the nitrogen cycle) have already been exceeded.

Approfondissement

Rockström et al. 2009a,
Ecology & Society

Research
Planetary Boundaries: Exploring the Safe Operating Space for Humanity

ABSTRACT. Anthropogenic pressures on the Earth System have reached a scale where abrupt global environmental change can no longer be excluded. We propose a new approach to global sustainability in which we define planetary boundaries within which we expect that humanity can operate safely. Transgressing one or more planetary boundaries may be deleterious or even catastrophic, due to the risk of crossing thresholds that will trigger non-linear, abrupt environmental change within continental- to planetary-scale systems. We have identified nine planetary boundaries and, drawing upon current scientific understanding, we propose quantitative targets for seven of them. These seven are climate change (CO₂ concentration in the atmosphere <350 ppm and/or a maximum change of +1 W m⁻² in radiative forcing); ocean acidification (mean surface oceanic saturation state with respect to aragonite >80% of pre-industrial levels); stratospheric ozone (<5% reduction in O₃ concentration from pre-industrial level of 290 Dobson Units); biogeochemical nitrogen (N) cycle (limit industrial and agricultural fixation of N₂ to 35 Tg N yr⁻¹); and phosphorus (P) cycle (annual P inflow to oceans not to exceed 10 times the natural background weathering of P₂O₅ global freshwater use <4000 km³ yr⁻¹ of consumptive use of runoff resources); land system change (<1% of the ice-free land surface under cropland); and the rate at which biological diversity is lost (annual rate <10 extinctions per million species). The two additional planetary boundaries for which we have not yet been able to determine a boundary level are chemical pollution and atmospheric aerosol loading. We estimate that humanity has already transgressed three planetary boundaries: for climate change, rate of biodiversity loss, and changes to the global nitrogen cycle. Planetary boundaries are interdependent, because transgressing one may both shift the position of other boundaries or cause them to be transgressed. The social impacts of transgressing boundaries will be a function of the social-ecological resilience of the affected societies. Our proposed boundaries are rough, first estimates only, surrounded by large uncertainties and knowledge gaps. Filling these gaps will require major advancements in Earth system and resilience science. The proposed concept of 'planetary boundaries' lays the groundwork for shifting our approach to governance and management, away from the essentially sectoral analysis of limits to growth aimed at minimizing negative externalities, toward the estimation of the safe space for human development. Planetary boundaries define, as it were, the boundaries of the 'planetary playing field' for humanity if we want to be sure of avoiding major human-induced environmental change on a global scale.

Key Words: atmospheric aerosol loading; biogeochemical nitrogen cycle; biological diversity; chemical pollution; climate change; Earth; global freshwater use; land system change; ocean acidification; phosphorus cycle; planetary boundaries; stratospheric ozone; sustainability

Approfondissement

Supplementary Information

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Supplementary Discussion

1. Dynamics of system change
2. Setting boundaries - comparison with other approaches
3. Extended description of the climate change boundary
4. Extended description of the global freshwater use boundary
5. Additional description of interactions between boundaries

Supplementary Methods

1. Method for identifying and defining planetary boundaries
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Fondements scientifiques

Global Environmental Change

Approaches to defining a planetary boundary for biodiversity

Rethinking Planetary Boundaries: Accounting for Ecological Limits

Help!

Quelle science derrière le concept ?

Dynamique des systèmes

Rockström et al., 2009

16th September 2009

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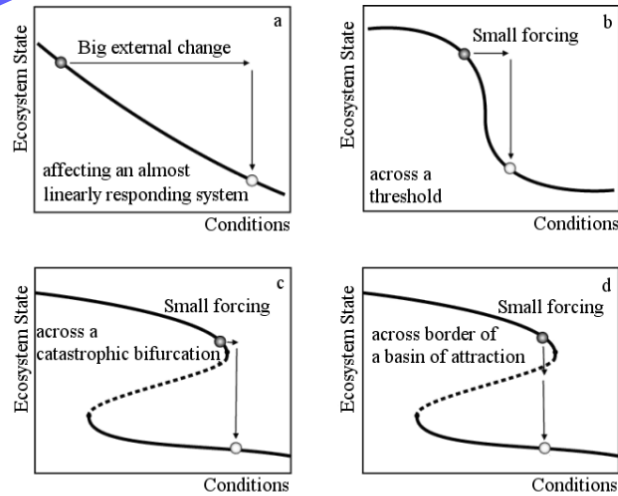
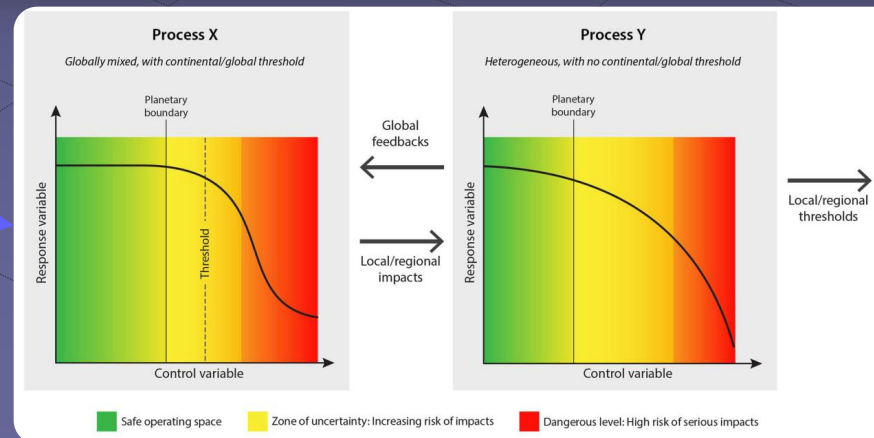


Figure S2. Degree of change in conditions required to generate large impacts in system state. For systems characterized by non-linear threshold dynamics a small forcing can generate large change, while systems responding largely linearly to change, will require big external change to cause large impacts. Source: Scheffer (2009).



Quelle science derrière le concept ?

Rockström et al. 2009b, Nature
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FEATURE

A safe operating space for humanity

Identifying and quantifying planetary boundaries that must not be transgressed could help prevent human activities from causing unacceptable environmental change, argue **Johan Rockström** and colleagues.

Although Earth has undergone many periods of significant environmental change, the planet's environment has been remarkably stable for the past 10,000 years. This period of stability – known to geologists as the Holocene – has seen human civilisations arise, develop and thrive. Such stability may now be under threat. Since the Industrial Revolution, a new era has arisen: the Anthropocene, in which human actions have become the main driver of global environmental change. This could see human activities push the Earth system outside the stable environmental state of the Holocene, with consequences that are detrimental to civilisation for large parts of the world. During the Holocene, environmental change occurred naturally and Earth's regulatory capacity maintained the conditions that enabled human development. Regular temperatures, freshwater availability and biogeochemical cycles stayed within a relatively narrow range. Now, largely because of rapid growing reliance on fossil fuels and industrialised forms of agriculture, human activities have reached a level that could damage the systems that keep Earth in the desirable Holocene state. The result could be irreversible and, in some cases, abrupt environmental change, leading to a state less conducive to human development. Without prompt human action, the Holocene is expected to continue for at least several thousand years. Planetary boundaries To meet the challenge of maintaining the Holocene state, we propose a framework based on 'planetary boundaries'. These boundaries define the safe operating space for humanity with respect to the Earth system and are associated with the planet's biophysical subsystems or processes. Although Earth's complex systems sometimes respond smoothly to changing pressures, it seems that this will prove to be the exception rather than the rule. Many subsystems of Earth react in a nonlinear, often abrupt, way and periodically revert around threshold levels of certain key variables. If these thresholds are crossed, then important subsystems, such as a common system, could shift into a new state, often with deleterious or potentially even disastrous consequences for humanity. Most of these thresholds can be defined by a critical value for one or more natural variables, such as carbon dioxide concentration. Not all processes or subsystems on Earth have well-defined thresholds, although human actions that undermine the resilience of such processes or subsystems – for example, land and water degradation – can increase the risk that thresholds will also be crossed in other processes, such as the climate system. We have tried to identify the Earth system processes and associated thresholds which, if crossed, could generate unacceptable environmental change. We have found nine such processes for which we believe it is necessary to define planetary boundaries: climate change, rate of biodiversity loss (terrestrial and marine), interference with the nitrogen and phosphorus cycles, stratospheric ozone depletion, ocean acidification, global freshwater use, change in land use, and chemical pollution and atmospheric aerosol loading (see Fig. 1 and Table). In general, planetary boundaries are values that control variables are either at a distance from thresholds – for processes with evidence of threshold behaviour – or at dangerous levels – for processes without

Approfondissement

Rockström et al. 2009a,
Ecology & Society

Research

Planetary Boundaries: Exploring the Safe Operating Space for Humanity

Johan Rockström^{1,2}, Will Steffen^{1,3}, Kevin Noone^{1,4}, Åke Persson^{1,2}, E. Stuart Chapin¹, Eric Lambin⁵, Timothy M. Lenton⁶, Martin Scheffer⁷, Carl Folke^{1,2}, Hans-Joachim Schellnhuber^{8,9}, Boris Goldy¹⁰, Cynthia A. de Wit¹¹, Terry Hughes¹², Stephen von Holst¹³, Ermarie Hobbie¹⁴, Sverker Starin¹⁵, Peter A. Snyder¹⁶, Robert Costanza¹⁷, Lisa Steffen¹, Malin Falkenmark¹⁸, Louisa Karlberg¹⁹, Robert W. Howarth²⁰, Dáire Ní Fheolaigh²¹, James Hansen²², Brian Walker²³, Diana Liverman²⁴, Katherine Richardson²⁵, Paul Crutzen²⁶, and Jonathan Lenoir

ABSTRACT. Anthropogenic pressures on the Earth System have reached a scale where abrupt global environmental change can no longer be excluded. We propose a new approach to global sustainability in which we define planetary boundaries within which we expect that humanity can operate safely. Transgressing one or more planetary boundaries may be deleterious or even catastrophic, due to the risk of crossing thresholds that will trigger non-linear, abrupt environmental change within continental-to-planetary-scale systems. We have identified nine planetary boundaries and, drawing upon current scientific understanding, we propose quantifications for seven of them. These seven are climate change (CO₂ concentration in the atmosphere <350 ppm and/or a maximum change of +1 W m⁻² in radiative forcing); ocean acidification (mean surface oceanic saturation state with respect to aragonite >200% of pre-industrial levels); stratospheric ozone (<5% reduction in O₃ concentration from pre-industrial level of 250 Dobson Units); biogeochemical nitrogen (N) cycle (limit industrial and agricultural fixation of N₂ to 55 Tg N yr⁻¹) and phosphorus (P) cycle (annual P inflow to oceans not to exceed 10 times the natural background weathering of P₂ global freshwater use <4000 km³ yr⁻¹ of consumptive use of runoff resources); land system change (<1% of the ice-free land surface under cropland); and the rate at which biological diversity is lost (annual rate of <10 extinctions per million species). The two additional planetary boundaries for which we have not yet been able to determine a boundary level are chemical pollution and atmospheric aerosol loading. We estimate that humanity has already transgressed three planetary boundaries: for climate change, rate of biodiversity loss, and changes to the global nitrogen cycle. Planetary boundaries are interdependent, because transgressing one may both shift the position of other boundaries or cause them to be transgressed. The social impacts of transgressing boundaries will be a function of the social-ecological resilience of the affected societies. Our proposed boundaries are rough, first estimates only, surrounded by large uncertainties and knowledge gaps. Filling these gaps will require major advancements in Earth system and resilience science. The proposed concept of 'planetary boundaries' lays the groundwork for shifting our approach to governance and management, away from the essentially sectoral analysis of limits to growth aimed at minimizing negative externalities, toward the estimation of the safe space for human development. Planetary boundaries define, as it were, the boundaries of the 'planetary playing field' for humanity if we want to be sure of avoiding major human-induced environmental change on a global scale.

Key Words: atmospheric aerosol loading; biogeochemical nitrogen cycle; biological diversity; chemical pollution; climate change; Earth; global freshwater use; land system change; ocean acidification; phosphorus cycle; planetary boundaries; stratospheric ozone; sustainability

Approfondissement

Rockström et al., 2009 16th September 2009

Supplementary Information

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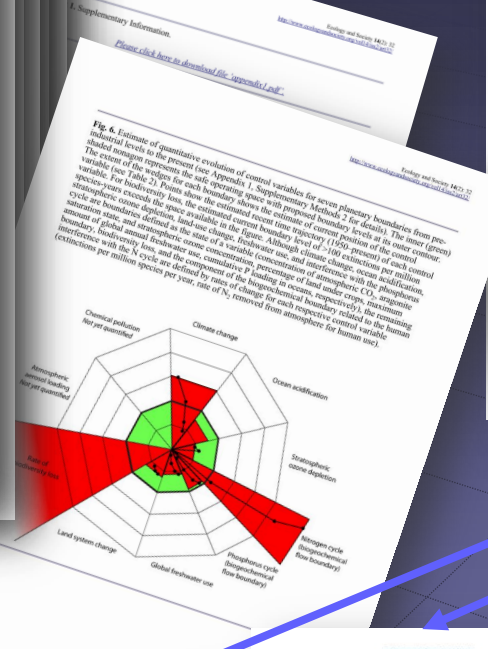
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Fondements scientifiques

Global Environmental Change

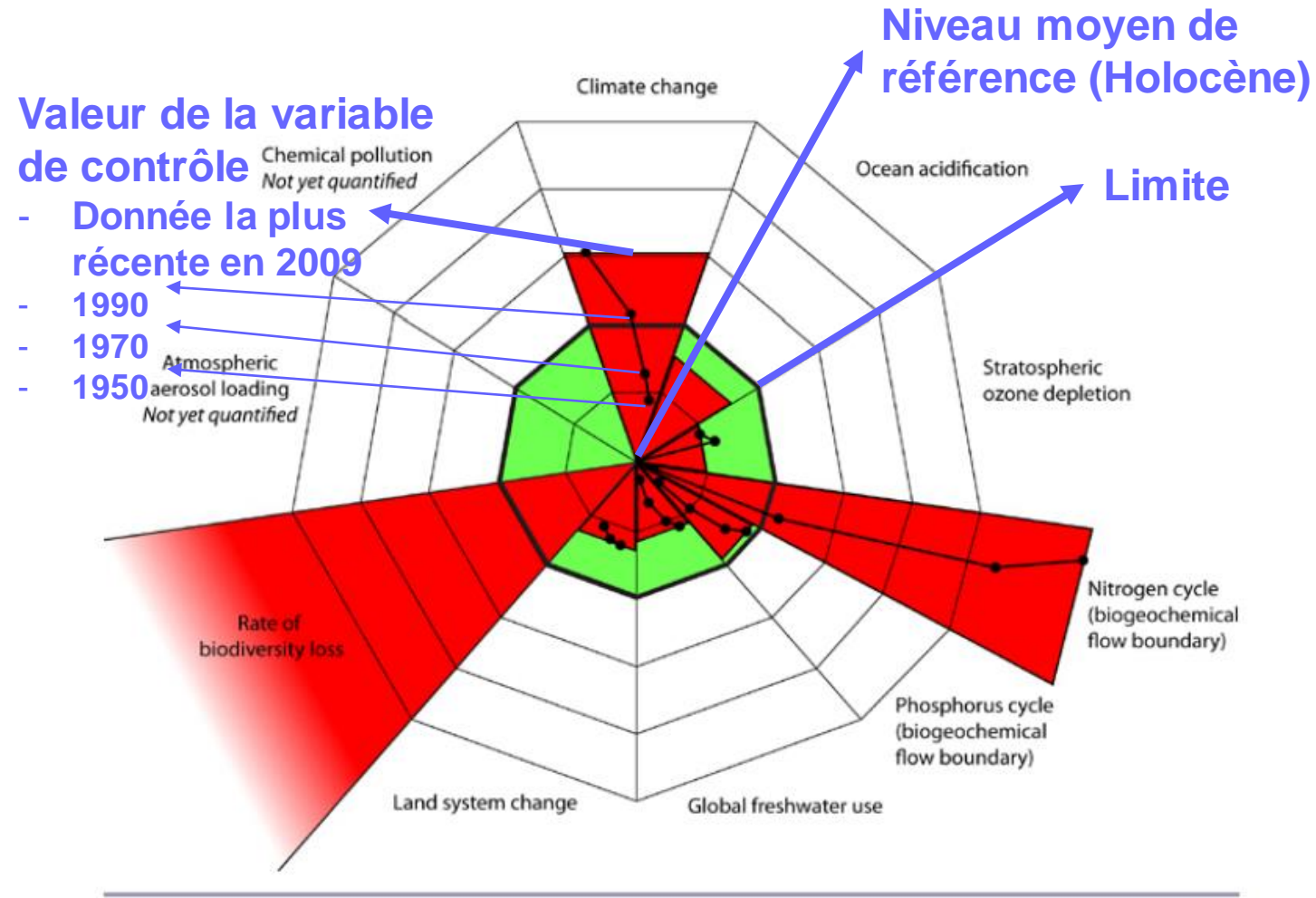
Approaches to defining a planetary boundary for biodiversity

Corina M. Mora^{1,2}, Betha Reyes^{3,4}, Bob Alward⁵, Bettina Beger⁶, E. Stuart Chapin III⁷, Sarah E. Cornell⁸, Linda Diaz⁹, Timon Jansen¹⁰, Paul Leadley¹¹, Peter A. Moilanen¹², Robert J. Scholes¹³, Anzar W.R. Siddons¹⁴, Martin Solan¹⁵, Will Steffen¹⁶, Guy Woodward¹⁷

ABSTRACT. The concept of planetary boundaries offers a framework for understanding and managing humanity's impact on Earth's ecological systems. These boundaries aim to delineate a safe operating space in which human activities must remain to avoid transgressing planetary boundaries, which would threaten the stability of critical human systems. We investigate an alternative approach to planetary boundaries, one that focuses on the concept of ecological resilience. We propose a framework for setting a boundary for biodiversity based on the concept of ecological resilience. We argue that this approach is more appropriate than the current approach based on species extinctions, and we provide a method for setting a boundary for biodiversity based on the concept of ecological resilience. We argue that this approach is more appropriate than the current approach based on species extinctions, and we provide a method for setting a boundary for biodiversity based on the concept of ecological resilience.

Quelle science derrière le concept?

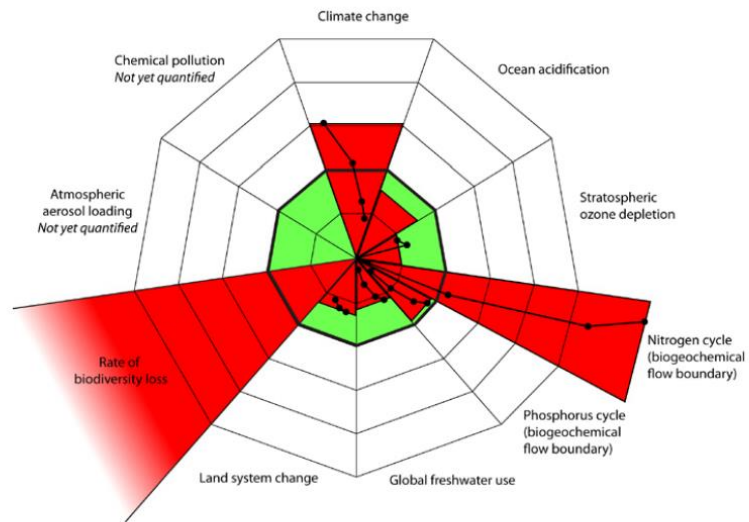
variable. For biodiversity loss, the estimated current boundary level of 100 extinctions per million species-years exceeds the space available in the figure. Although climate change, ocean acidification, stratospheric ozone depletion, land-use change, freshwater use, and interference with the phosphorus cycle are all within the space available, the estimated current boundary level for atmospheric CO_2 , aragonite saturation, and stratospheric ozone concentration, respectively, are close to the boundary. The remaining amount of global annual freshwater use, cumulative P loading in oceans, respectively, the remaining boundary, biodiversity loss, and the component of the biogeochemical boundary related to the human interference with the N cycle are defined by rates of change for each respective control variable (extinctions per million species per year, rate of N_2 removed from atmosphere for human use).



Quelle science derrière le concept ?

Ecology and Society 14(2): 32
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Fig. 6. Estimate of quantitative evolution of control variables for seven planetary boundaries from pre-industrial levels to the present (see Appendix 1, Supplementary Methods 2 for details). The inner (green) shaded nonagon represents the safe operating space with proposed boundary levels at its outer contour. The extent of the wedges for each boundary shows the estimate of current position of the control variable (see Table 2). Points show the estimated recent time trajectory (1950–present) of each control variable. For biodiversity loss, the estimated current boundary level of >100 extinctions per million species-years exceeds the space available in the figure. Although climate change, ocean acidification, stratospheric ozone depletion, land-use change, freshwater use, and interference with the phosphorus cycle are boundaries defined as the state of a variable (concentration of atmospheric CO₂, aragonite saturation state, and stratospheric ozone concentration, percentage of land under crops, maximum amount of global annual freshwater use, cumulative P loading in oceans, respectively), the remaining boundary, biodiversity loss, and the component of the biogeochemical boundary related to the human interference with the N cycle are defined by rates of change for each respective control variable (extinctions per million species per year, rate of N₂ removed from atmosphere for human use).



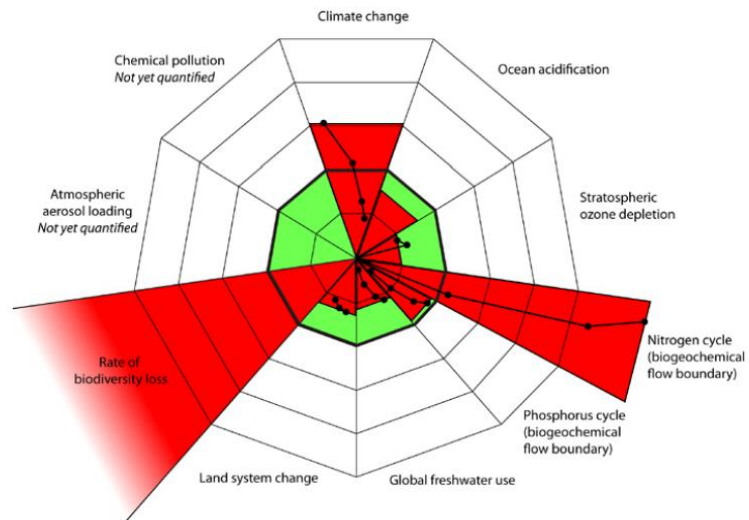
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Earth system process	Control variable	Boundary	Pre-industrial*	1950	1970	1990**	Latest data
Climate change	Atmospheric CO ₂ concentration, ppm	350	280	311	326	354	387
Ocean acidification	Global oceanic aragonite saturation ratio	2.75	3.44	n.a.	n.a.	n.a.	2.90
Stratospheric ozone depletion	Stratospheric O ₃ concentration, DU	276	290	n.a.	292	282	283
Nitrogen cycle (Part of a single biogeochemical flow boundary)	Amount of N ₂ removed from the atmosphere for human use, Mt yr ⁻¹	35	0	4	39	98	121
Phosphorus cycle (Part of a single biogeochemical flow boundary)	Quantity of P flowing into the oceans, Mt yr ⁻¹	11	1.1	3.4	6.0	8.5	10.3 (9) ****
Global freshwater use	Consumptive use of withdrawn runoff, km ³ yr ⁻¹	4,000	415	887	1,536	2,192	2,600
Land system change	Percentage of global land cover converted to cropland, % (Mha)	15 (1,995)	5 (665)	n.a.	10.71 (1,424)	11.45 (1,522)	11.68 (1,554)
Biodiversity loss	Extinction rate in number of species per million per year, E/MSY	10	1	n.a.	n.a.	n.a.	>100
Atmospheric aerosol loading	Not yet quantified	-	-	-	-	-	-
Chemical pollution	Not yet quantified	-	-	-	-	-	-

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Variable de contrôle

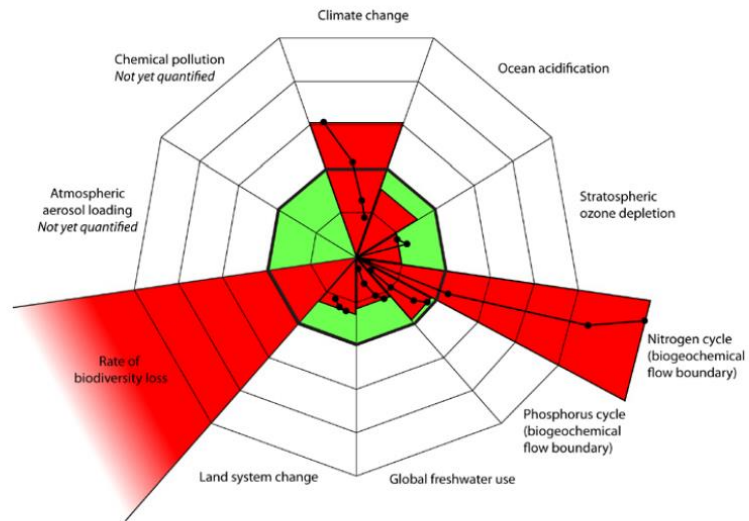
Choisis à dire d'expert

- Au sein du consortium scientifique
- Workshops avec communauté plus large et échange avec décideurs du secteur privé, gouvernementaux et société civile

Quelle science derrière le concept ?

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Chemical pollution	Not yet quantified	-	-	-	-	-	-

Valeurs

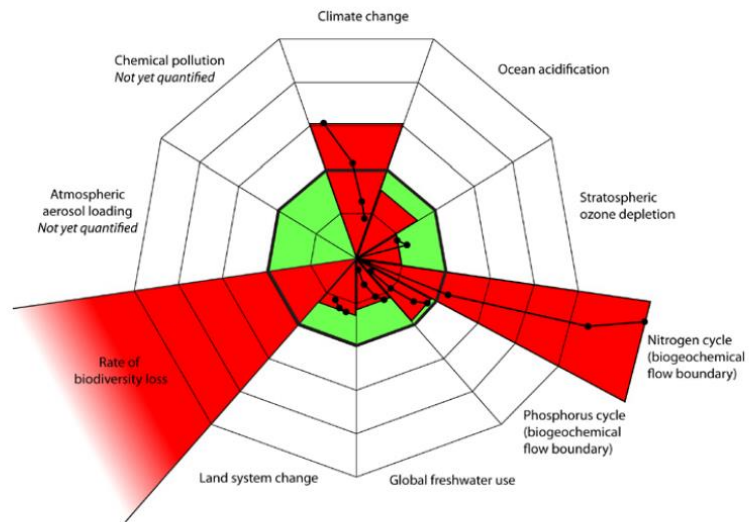
Quantification basée sur

- Littérature scientifique
- Analyses spécifiques conduites au sein du consortium

Quelle science derrière le concept ?

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Chemical pollution	Not yet quantified	-	-	-	-	-	-

Limites

Quantification arbitraires

Subjectivité basée sur:

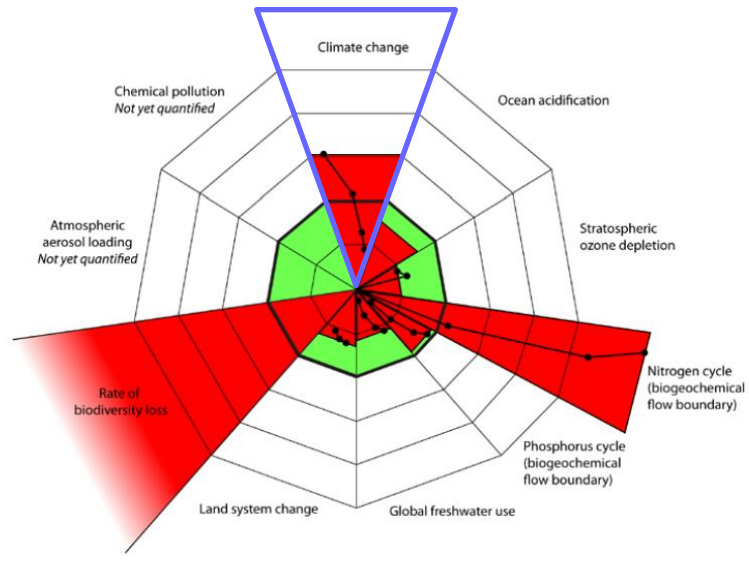
- La capacité des sociétés à gérer le risque et les incertitudes
- L'espace entre le seuil critique et la limite « safe » doit être
 - suffisamment court pour qu'il y ait un intérêt à agir
 - suffisamment éloigné pour avoir une marge de manœuvre

Quelle science derrière le concept ?

Climate Change

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Variable de contrôle	Seuil critique	Limite (safe)	Valeur (2009)
Concentration atmosphérique CO ₂ (ppm)	350-450 ppm	350ppm	387 ppm

Sur la base des travaux paléoclimatiques (Hansen et al. 2008)

- **Variables de réponse**
 - Calottes polaires
 - Température du globe
- **Effet sur la température globale**
 - **Rétroaction rapides**
 - Modèle de climat IPCC (2007): [CO₂]_{x2} → ΔT ~ + 3°C
 - **Rétroactions lentes**
 - Entre -20000 ans et -10000 ans: [CO₂]_{x2} → ΔT ~ + 6°C
- **Seuils réversibilité des calottes**
 - Sur les dernières 65 millions d'année oscillations calottes polaires montre une réversibilité possible entre 350-550 ppm
 - Pas de consensus sur risque hystérésis

Sur la base des observations contemporaines (réf. Multiples)

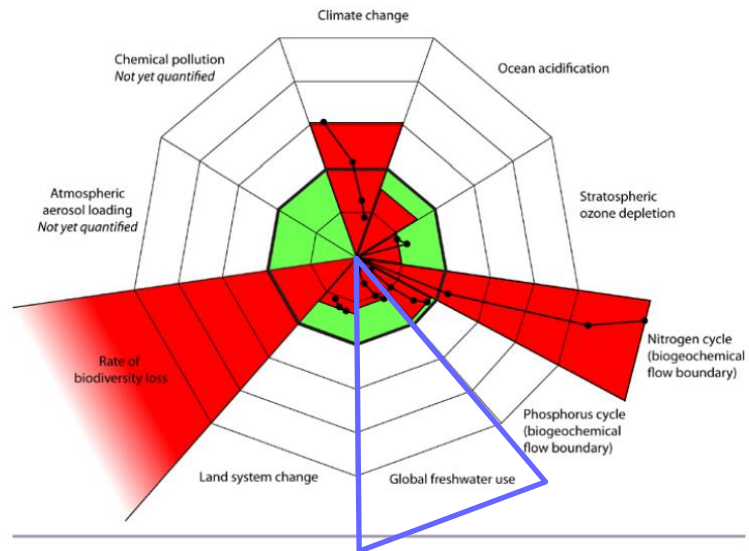
- **Variables de réponse multiples**
 - **Rétroactions rapides**
 - Retrait rapide de la banquise
 - Retrait des glaciers partout dans le monde et des calottes
 - Un décalage vers le nord de la cellule de Hadley avec augmentation de l'aridité de certaines régions (Méditerranée, Sud USA, Est Australie et une partie de l'Afrique)
 - Blanchissement et mortalité des coraux
 - Accélération du taux d'augmentation du niveau marin
 - Augmentation du nombre d'inondation
 - **Rétroactions lentes se mettent en place**
 - En lien avec le cycle du carbone et le changement d'albedo

Quelle science derrière le concept ?

Global freshwater use

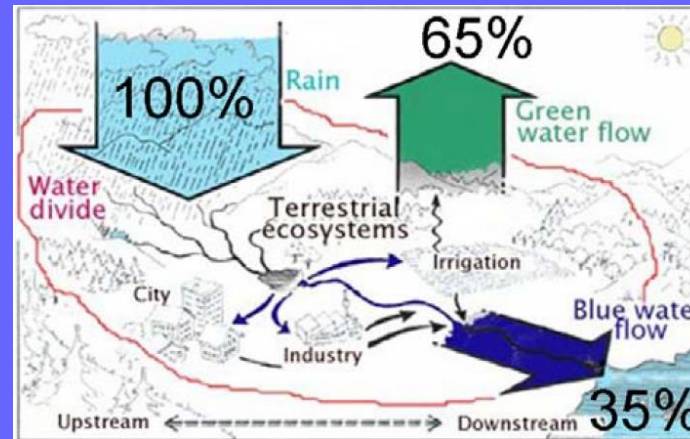
Ecology and Society 14(2): 32
<http://www.ecologyandsociety.org/vol14/iss2/art32/>

Fig. 6. Estimate of quantitative evolution of control variables for seven planetary boundaries from pre-industrial levels to the present (see Appendix 1, Supplementary Methods 2 for details). The inner (green) shaded nonagon represents the safe operating space with proposed boundary levels at its outer contour. The extent of the wedges for each boundary shows the estimate of current position of the control variable (see Table 2). Points show the estimated recent time trajectory (1950–present) of each control variable. For biodiversity loss, the estimated current boundary level of >100 extinctions per million species-years exceeds the space available in the figure. Although climate change, ocean acidification, stratospheric ozone depletion, land-use change, freshwater use, and interference with the phosphorus cycle are boundaries defined as the state of a variable (concentration of atmospheric CO₂, aragonite saturation state, and stratospheric ozone concentration, percentage of land under crops, maximum amount of global annual freshwater use, cumulative P loading in oceans, respectively), the remaining boundary, biodiversity loss, and the component of the biogeochemical boundary related to the human interference with the N cycle are defined by rates of change for each respective control variable (extinctions per million species per year, rate of N₂ removed from atmosphere for human use).



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Variable de contrôle	Seuil critique	Limite (safe)	Valeur (2009)
Prélèvement Eau Bleue	4000 – 6000 km ³ /an	4000 km ³ /an	2600 km ³ /an



Sur la base de littérature (réf. Multiples)

- Risque de collapse des plusieurs systèmes biologiques régionaux d'ampleur
 - En lien avec l'eau verte: e.g. Forêt amazonienne, désertification régionales
 - En lien avec l'eau bleue: Ecosystème rivières, Ecosystèmes marins, côtiers, estuaires et lacustres

• Deux variables de contrôle identifiées

- Eau verte
- Eau bleue

• Variables de réponse

Humidité du sol, production de biomasse, Séquestration de carbone, écosystèmes
 Lien directs avec changement climatique, usage des terre et biodiversité

Sur la base de littérature (réf. Multiples)

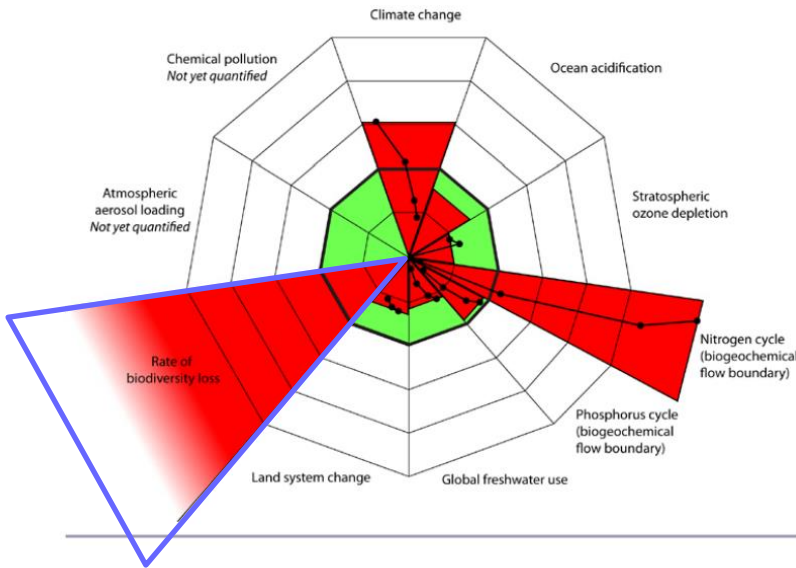
- Identification de seuils à risques pour l'eau bleue (uniquement considérée ici)
 - Danger pour les écosystèmes si prélèvement en rivière compris entre 4000 et 6000 km³
 - **Assèchement de 25% rivières**
 - **30-35% population risque de manquer d'eau**

Quelle science derrière le concept ?

Rate of biodiversity loss

Ecology and Society 14(2): 32
<http://www.ecologyandsociety.org/vol14/iss2/art32/>

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Variable de contrôle	Seuil critique	Limite (safe)	Valeur (2009)
Taux d'extinction en extinctions par million d'espèces par an (E/MSy)	Non défini	10 E/MSy	>100 E/MSy

Sur la base de la littérature (réf. Multiples)

• Variables de réponse Multiples

• Effets

- Variable lente affecte fonctionnement des écosystèmes à l'échelle du continent et des océans
- Impact sur de nombreuses autres processus – stockage Carbone, eau douce, cycles de l'azote et du phosphore, systèmes terrestres.
- Perte massive de biodiversité, inacceptable pour des raisons éthiques.

• Seuils non définis

- Existent à l'échelle locale
- Manque de connaissances pour être défini à l'échelle globale

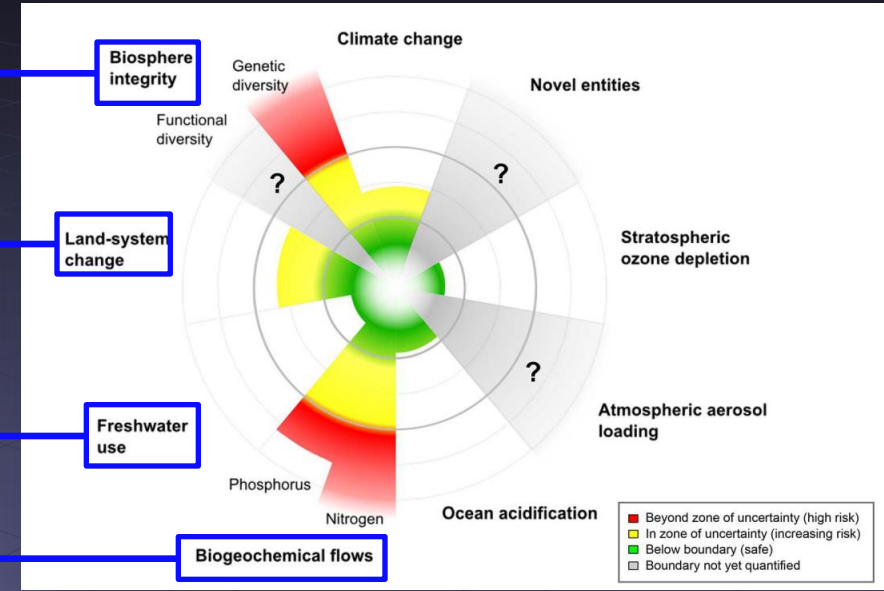
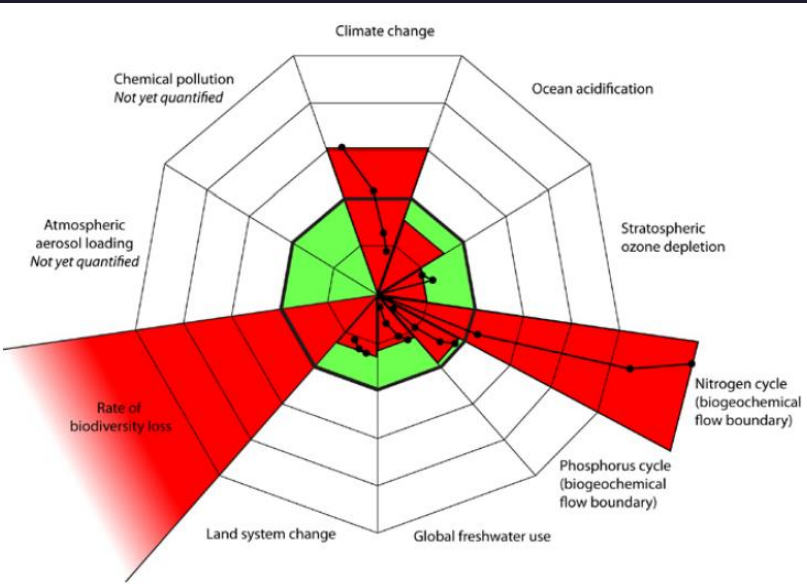
• Choix de la limite

- 10 E/MSy estimation incertaine d'un seuil moyen global Holocène
- Dépassé quoi qu'il en soit

Evolution des limites planétaires

Rockström et al. 2009, *Ecology & Society*

Steffen et al. 2015, *Science*



Inchangé (sauf valeur récente)

- Climate Change
- Stratospheric Ozone depletion
- Ocean acidification

Chgt noms de processus

- Biosphere integrity
- Biogeochemical flows

Chgt variables de contrôle

- Genetic diversity
- Function diversity

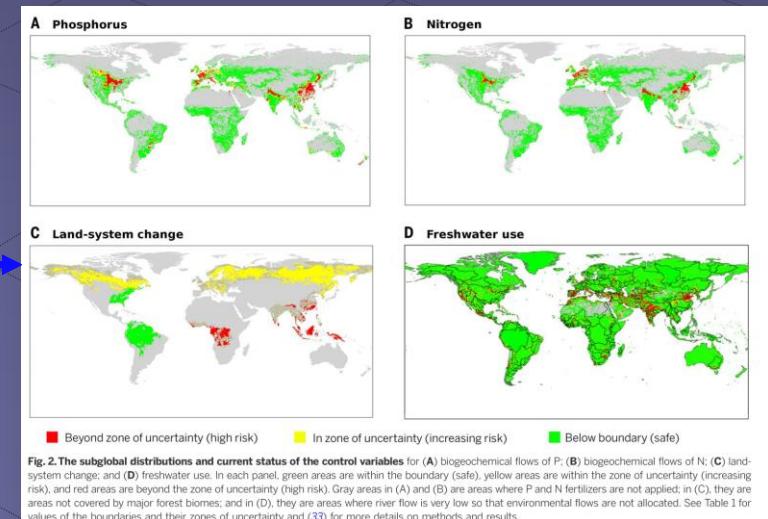
Chgt estimation des seuils

- Phosphore/Nitrogen
- Land system change

Mise en garde

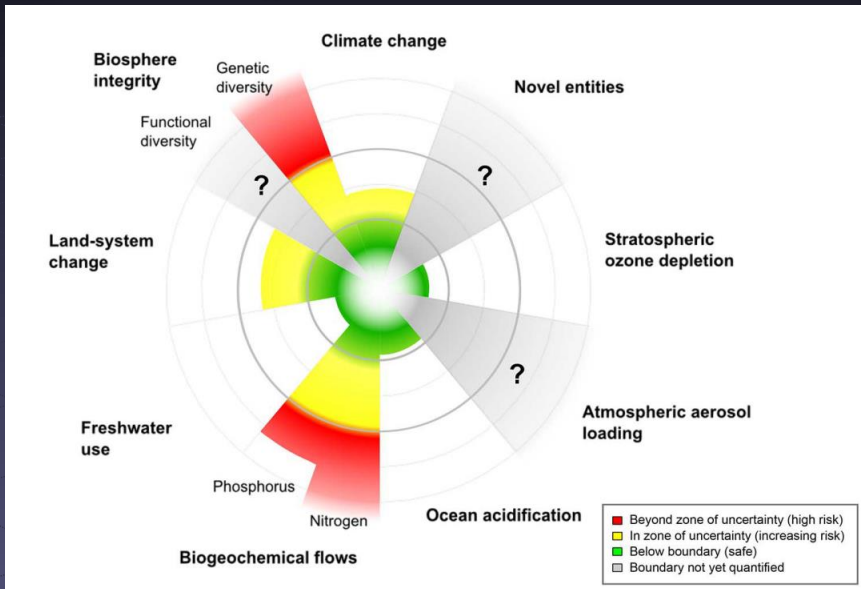
- Hiérarchisation
- Pas prévu pour usage à échelle nationale ou locale
- « Planetary Boundary thinking » reste à élaborer à ces échelles

Proposition de seuils régionaux

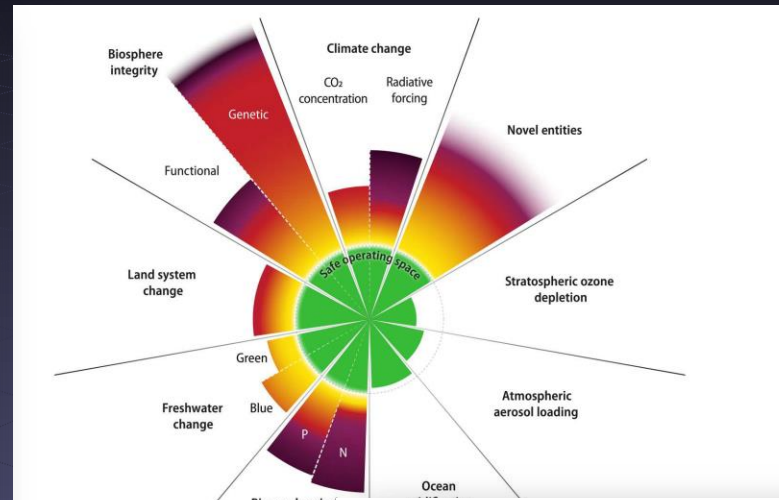


Evolution des limites planétaires

Steffen et al. 2015, Science



Richardson et al. 2023, Science Advances



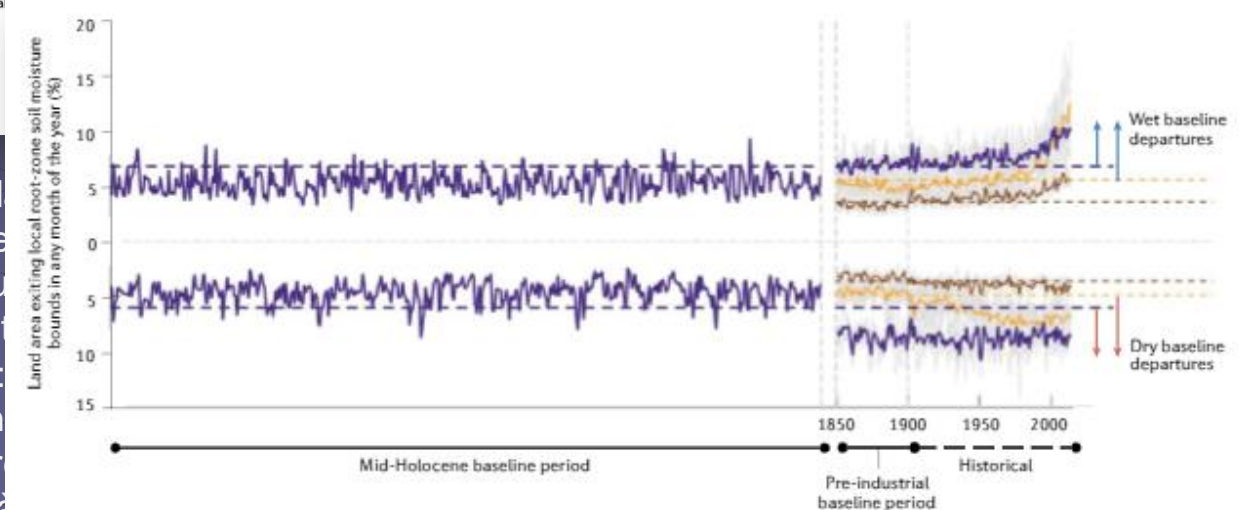
Fresh water défini de façon plus lisible.

- **Variables de contrôle**
 - proxys séparés de blue et green water
 - Évaluation de la déviation temporelle de la variabilité par rapport à l'Holocène
- **Seuil**
 - Le seuil est défini au 95th percentile de la variabilité naturelle et la variabilité sort de cette zone pour près de 20% de la zone continentale et ce depuis le début du XXème siècle.

Tous les processus et variables sont documentés

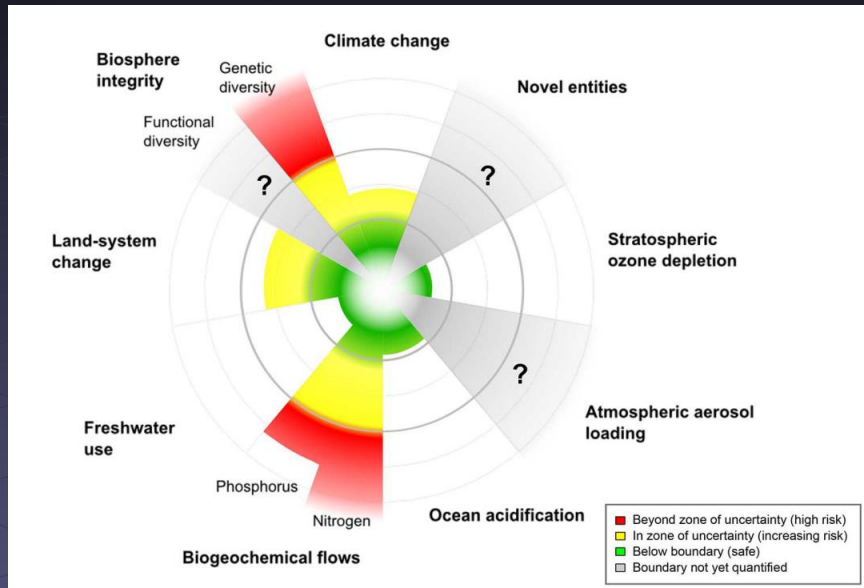
Changement de

- La notion de seuil est remplacée u d'augmentation d'augmentation Par exemple: correspond impacts tr → Coller à la terminologie et la sémologie du GIEC
- Mais le passage à haut risque reste extrêmement difficile à définir....

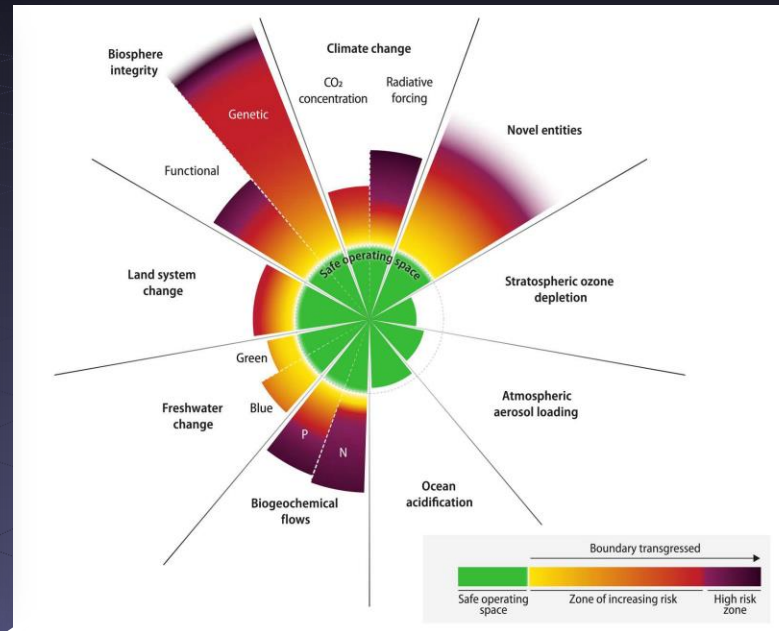


Evolution des limites planétaires

Steffen et al. 2015, Science



Richardson et al. 2023, Science Advances



Tous les processus et variables sont documentés

Changement dans la représentation

- La notion de zone d'incertitude est remplacée une zone d'augmentation des risques.
Par exple: 350-450ppm correspond à 1°-2° avec des impacts très différents.
→ Coller à la terminologie et la sémologie du GIEC
- Mais le passage à haut risque reste extrêmement difficile à définir....

Fresh water défini de façon plus lisible.

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Functional Biodiversity

- Variable de Contrôle**
 - Human Appropriation of Net Primary Production (appropriation de l'énergie qui ne peut pas être utilisée par la biosphère pour la photosynthèse) lié à agriculture, sylviculture, pâturage. Part augmente 15.7% en 1950 23.5% en 2020.
- Seuil**
 - comme pour beaucoup de limites sans seuil, il est considéré par accumulation de preuves (ici la diminution de la végétation naturelle) Limite fixée à 10% ce qui a débuté au 19eme siècle

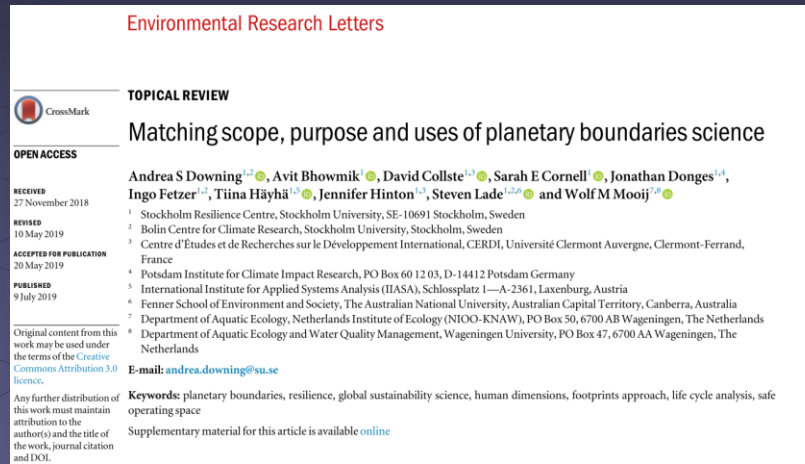
Critiques du concept dans le milieu académique

Littérature scientifique

Critiques constructives

- Choix de processus
- Choix des variables considérées non représentative du processus souvent trop réducteur de la complexité
- Mauvaise estimation des variables.
- Mauvaise prise en compte des interactions entre processus
- Choix des seuils qui cachent des sous-seuils régionaux non représentés.
- Incompatibilité du concept aux problématiques locales et régionales
- Subjectivité des limites basées sur des critères influencés par le contexte socio-économique (capacité à appréhender le risque)
- L'espace « safe » ne garantit par le bien-être
- ...

Le concept est accepté
→ Proposition pour améliorer/ajuster/modifier



Downing *al.* 2019, ERL

120 commentaires autour du concept

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- ...

Critiques anti-PB

- Il n'y a que de l'arbitraire
- Les indicateurs ne sont pas pertinents
- Les limites reposent sur la définition de tipping point dont l'existence n'est pas scientifiquement avérée
- Les processus sont des boîtes noires dont la complexité est ignorée
- Les concepts sont flous non objectivés
- Le choix du vocabulaire repose souvent sur l'émotionnel
- Risque de décrédibiliser les scientifiques auprès des décideurs
- Ignore les initiatives communautaires dans lequel il y a une vraie construction de consensus scientifique et une interaction avec les acteurs (IPBES)
- ...

In their final reply to Montoya et. al's criticism of the planetary boundaries framework, Rockström, Richardson and Steffen characterize the exchange with Montoya et. al. as doubly frustrating because the criticism is factually wrong and because "there is more that unites us than divides us." Illustrations: F. Pharaud, Deschênes/Globia

PLANETARY BOUNDARIES

A doubly frustrating exchange

A final reply to Montoya et. al's criticism of the planetary boundaries framework

Rockström et al. 2018b

The notion of a 'safe operating space for biodiversity' is vague and encourages harmful policies. Attempts to fix it strip it of all meaningful content. Ecology is rapidly gaining insights into the connections between biodiversity and ecosystem stability. We have no option but to understand ecological complexity and act accordingly.

Montaya et al. 2018a, Trends in Ecology and Evolution

A fundamental misrepresentation of the Planetary Boundaries framework

Responding to recent criticism, the main authors behind the framework explain how Planetary Boundaries does not rely on an assumption of thresholds or "tipping points" in the biosphere

Rockström et al. 2018a



Montaya et al. 2018b, Trends in Ecology and Evolution

Critiques du concept dans le milieu académique

Littérature scientifique

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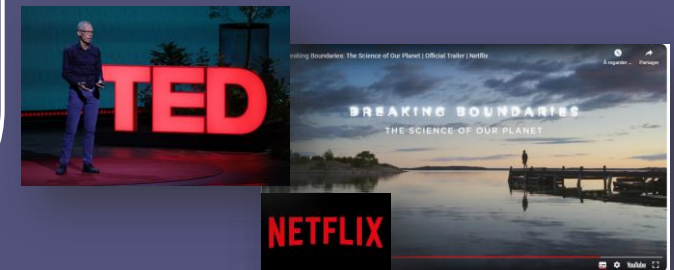
Réseaux sociaux/couloirs

Ressentis/Commentaires

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+

- Consortium fermé – auto-citation
- Principalement un outil de comm'



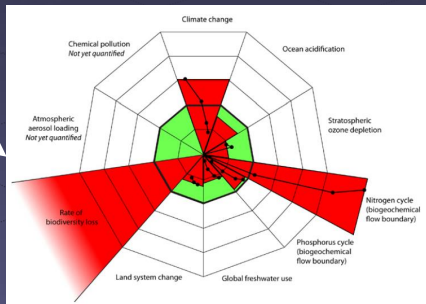
Un concept au succès planétaire sans limites...



“In 2007 Bo Ekman [Tällberg Foundation] made the point that Earth is always the missing ‘stakeholder’ around any negotiation table — be it climate, trade, or finance,” explains Rockström. “So, his idea was to create a big (like ten metres in diameter) round table, have Earth depicted visually as the “cloth” and run a negotiation with actors from business, culture, science, politics, etc., over how to govern humanity’s future on Earth.



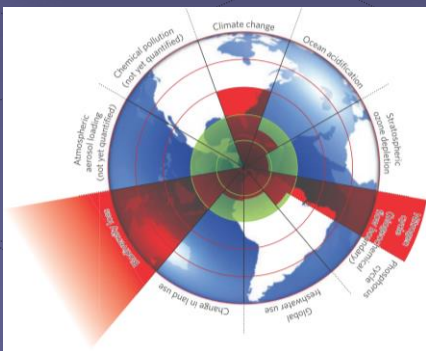
Rockström et al. 2009a



nature

Offre une vitrine
pour un résumé
non-reviewé
+
Retravaille le
diagramme

Understandable
Meaningful
Engaging



Rockström et al. 2009b

Environmental Science and Policy 78 (2017) 40–48

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

Analysing the influence of visualisations in global environmental governance

Piero Morseletto

Institute for Environmental Studies (IVM), Faculty of Earth and Life Sciences, VU University Amsterdam, 1081 HV Amsterdam, The Netherlands

Un concept au succès planétaire sans limites...



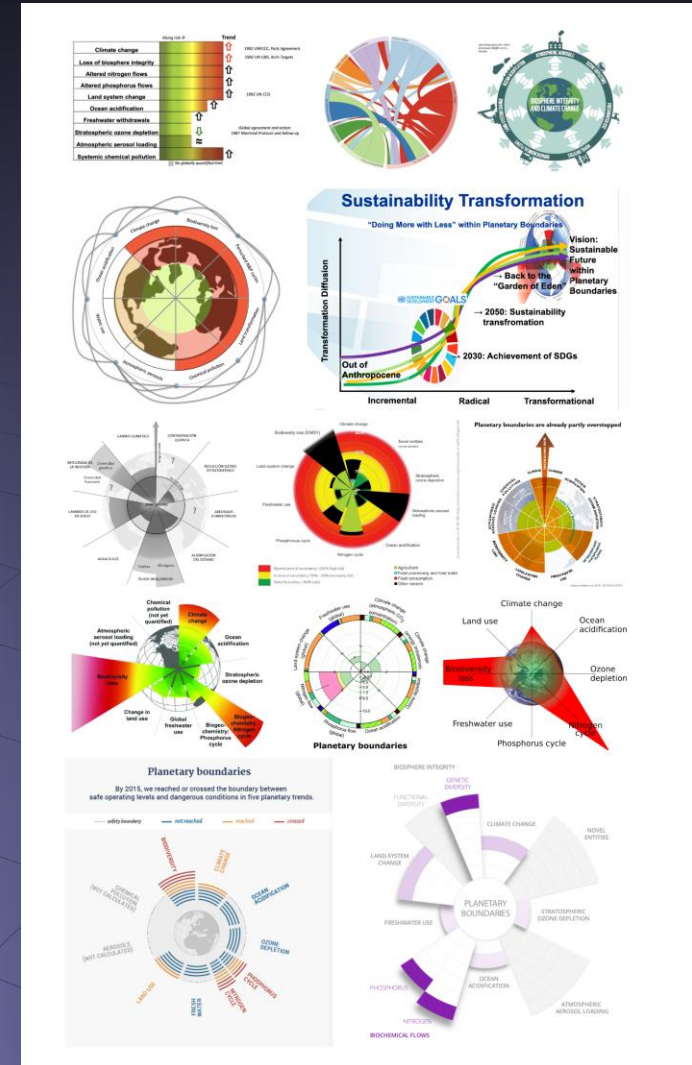
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Médiatique

- ONG
- Journaux
- Médias en ligne

Google Image
« Planetary boundaries »



Impact immédiat

Académique

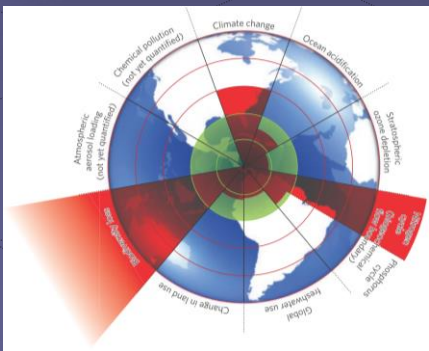
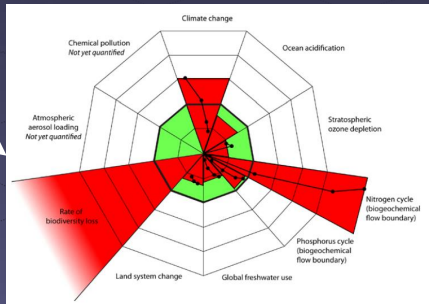
- Commentaires (>120 publications)
- Citations (>8800 citations)

nature

Offre une vitrine pour un résumé non-reviewé + Retravaille le diagramme

Understandable Meaningful Engaging

Rockström et al. 2009a



Rockström et al. 2009b

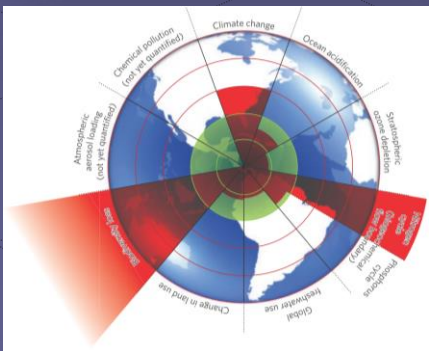
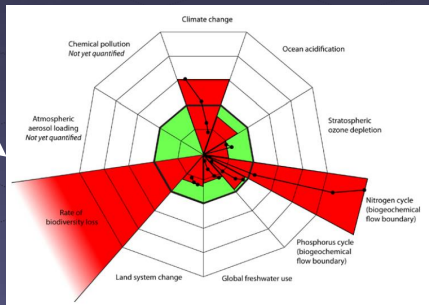
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Rockström et al. 2009a



Rockström et al. 2009b

nature

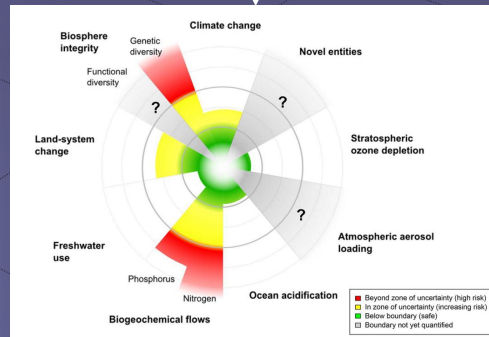
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Impact immédiat

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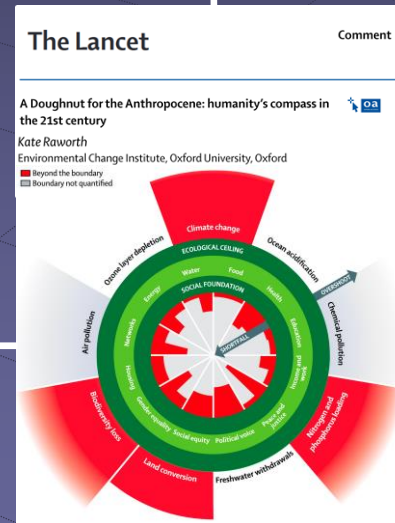
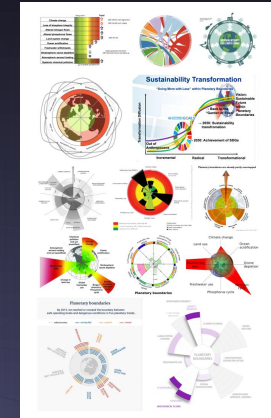


Steffen et al. 2015

Médiatique

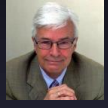
- ONG
- Journaux
- Médias en ligne

Google Image « Planetary boundaries »



Raworth 2017

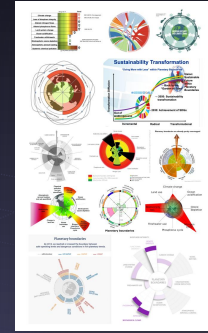
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Google Image
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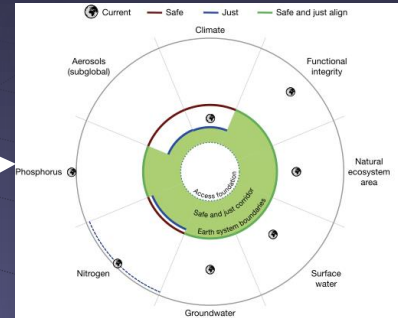


- Médiatique
- ONG
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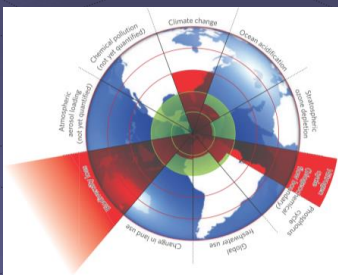
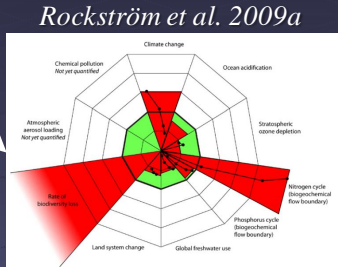
Impact immédiat

- Académique
- Commentaires (>120 publications)
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Intégration socio-économique
Safe and just space



Rockström et al. 2023, Nature
Gupta et al. 2024, The Lancet Planetary

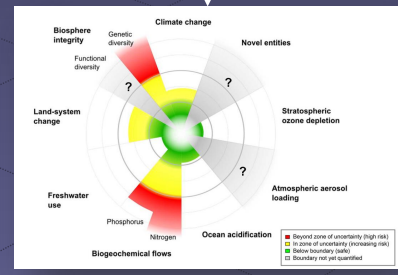


Rockström et al. 2009b

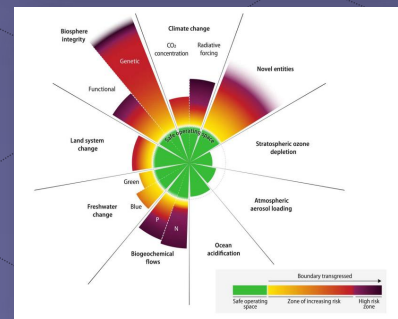
nature

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Understandable
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Steffen et al. 2015



Richardson et al. 2023



Raworth 2017

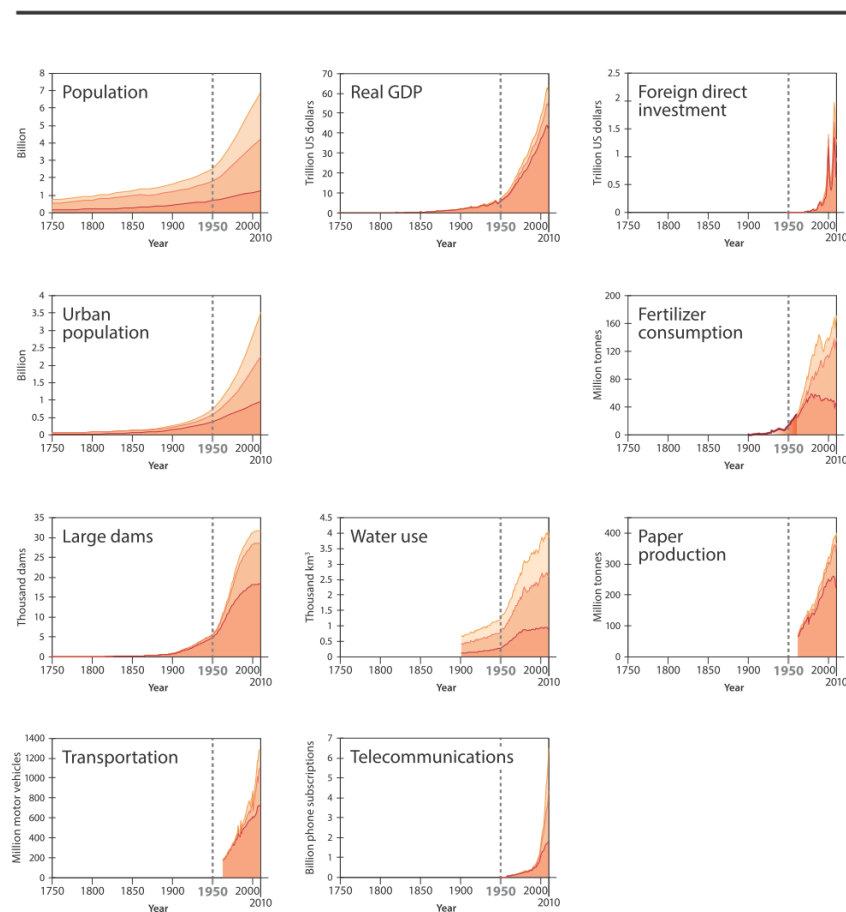
Applications Régionales

Au-delà du débat?

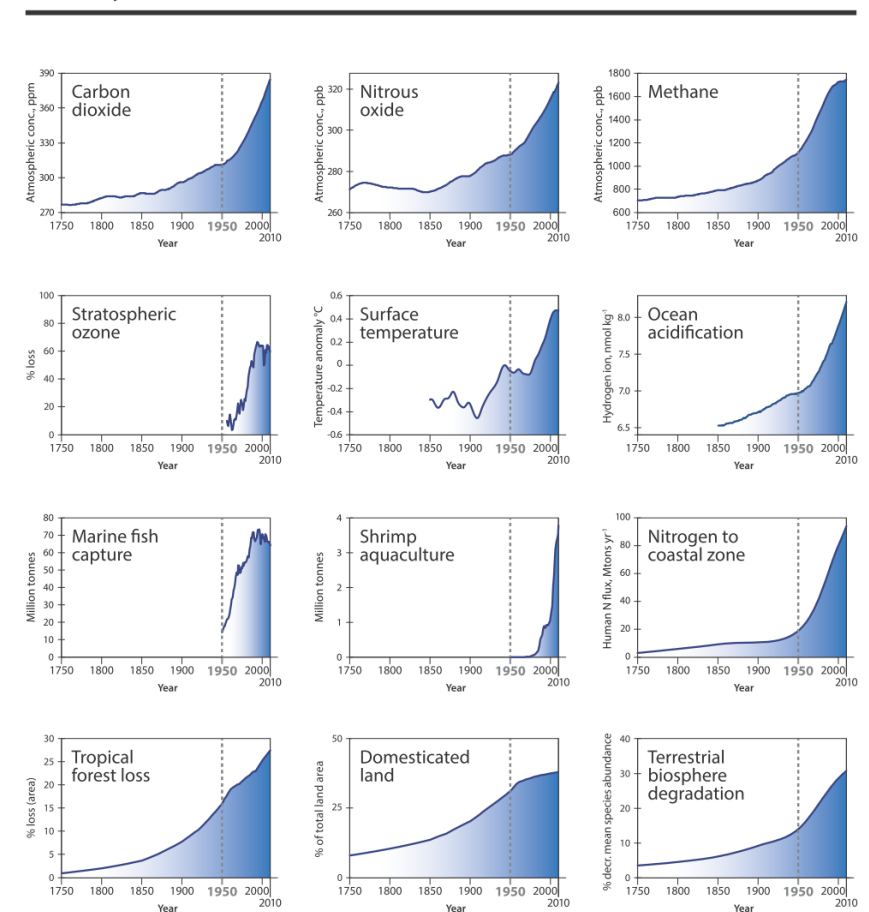
The trajectory of the Anthropocene: The Great Acceleration

Steffen et al. 2015, *The Anthropocene review*

Socio-economic trends

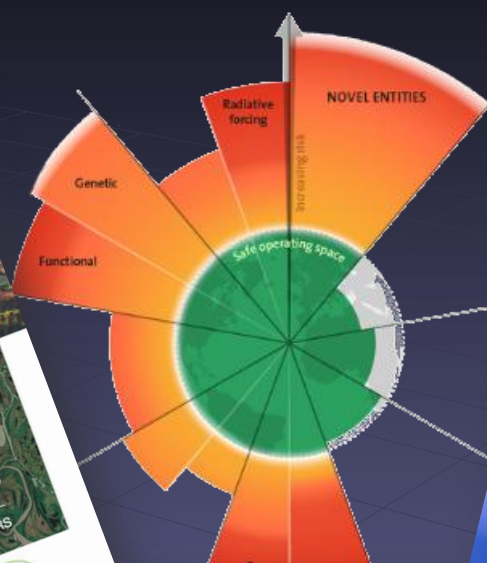
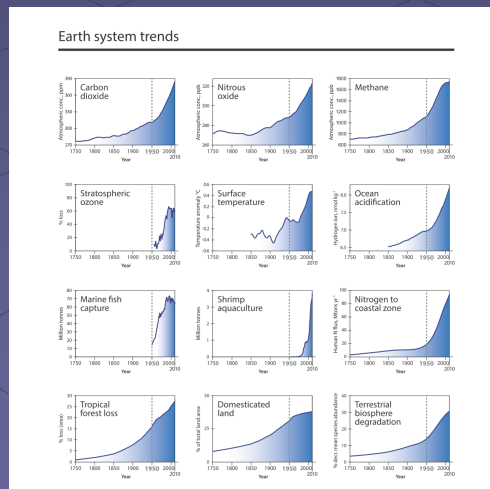
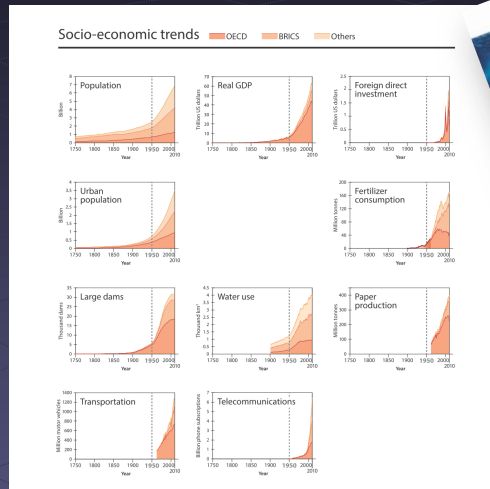


Earth system trends



Au-delà du débat?

- Lien thématique
- Approche systémique



Comment
Climate tipping points – too risky to bet against

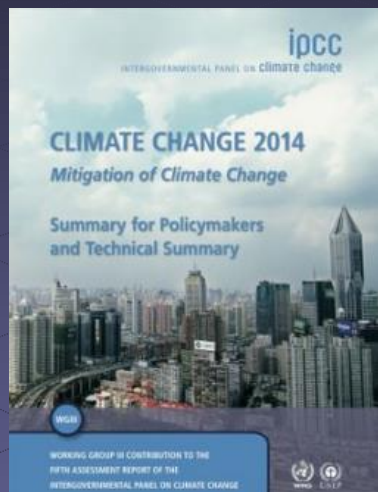
The growing threat of abrupt and irreversible climate changes must compel political and economic action on emissions.

Abstract
The growing threat of abrupt and irreversible climate changes must compel political and economic action on emissions. This report synthesizes the findings of the IPCC Working Group II contribution to the Sixth Assessment Report (AR6) Synthesis Report (SR1.9). It highlights the need for urgent action to limit global warming to 1.5°C, as the risk of crossing critical climate tipping points increases significantly above this level. The report also discusses the potential for cascading tipping points and the need for a just transition to a sustainable future.

Lenton et al. 2018

Au-delà du débat?

Atténuation



Adaptation



• Climatologie

*Cycle de l'eau
Un objet d'étude
à l'interface
climat-hydrologie
Société*

• Hydrologie

Malatténuation



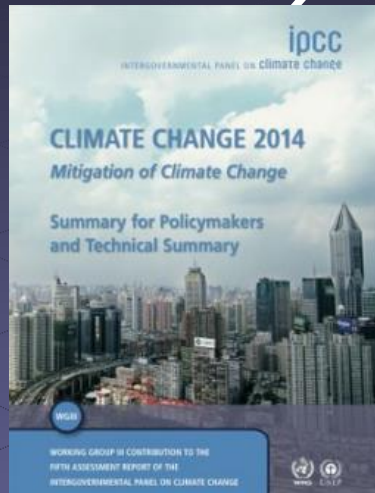
- Lien thématique
- Approche systémique



Maladaptation

Au-delà du débat?

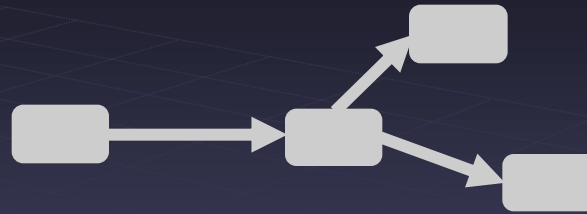
Atténuation



Malatténuation



Pensée en silo



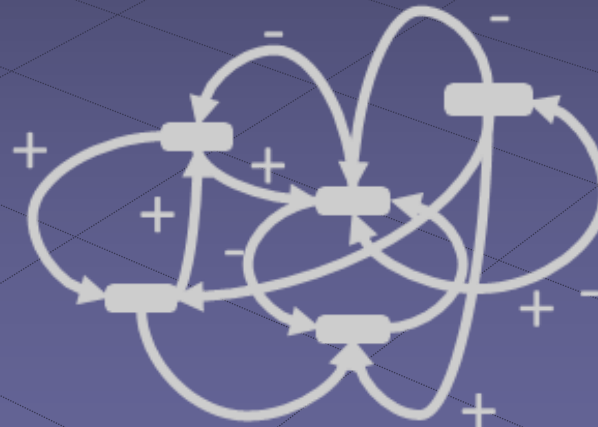
Adaptation



Maladaptation



Pensée systémique



- Lien thématique
- Approche systémique

Approche en silo



Fleuve Sénégal
La brèche de Saint Louis

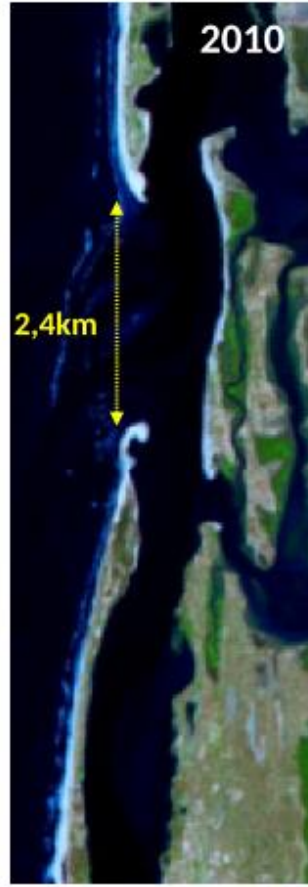
4 octobre 2003: 4 m de largeur



6 oct. 2003: 200 m



Approche en silo



Source: DIENG (2013)

Fleuve Sénégal La brèche de Saint Louis

Remède pire que le mal:
salinisation des terres par
incursion d'eau de mer.

Approche en silo

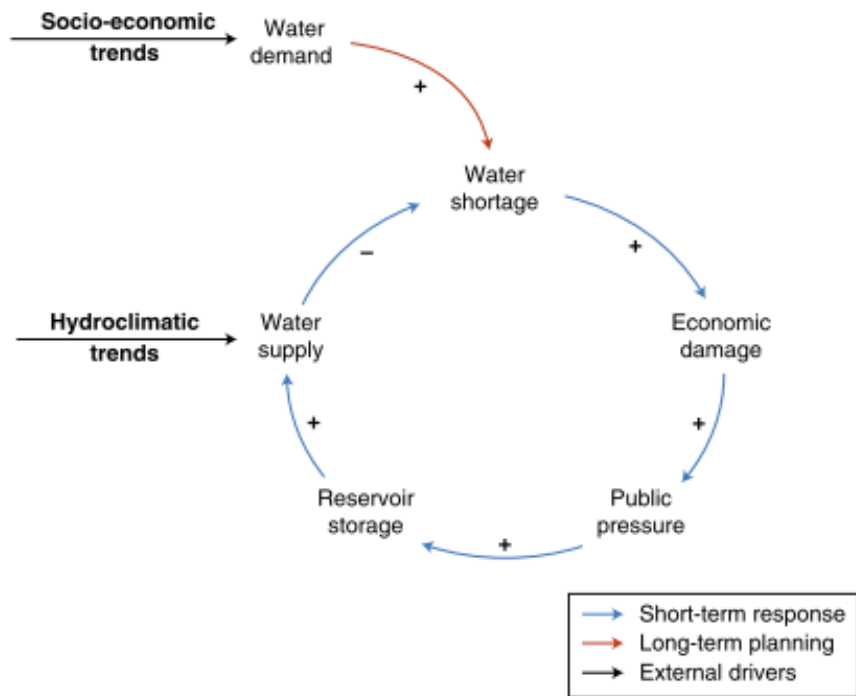


Fig. 1 | Water supply to cope with water shortage. The causal loop diagram shows the positive (+) and negative (-) feedbacks between physical, technical and social processes. This diagram is based on traditional approaches in water management and long-term planning that emphasize the role of external drivers of change (black arrows): socioeconomic trends influencing water demand and hydroclimatic trends influencing water supply.

Approche systémique

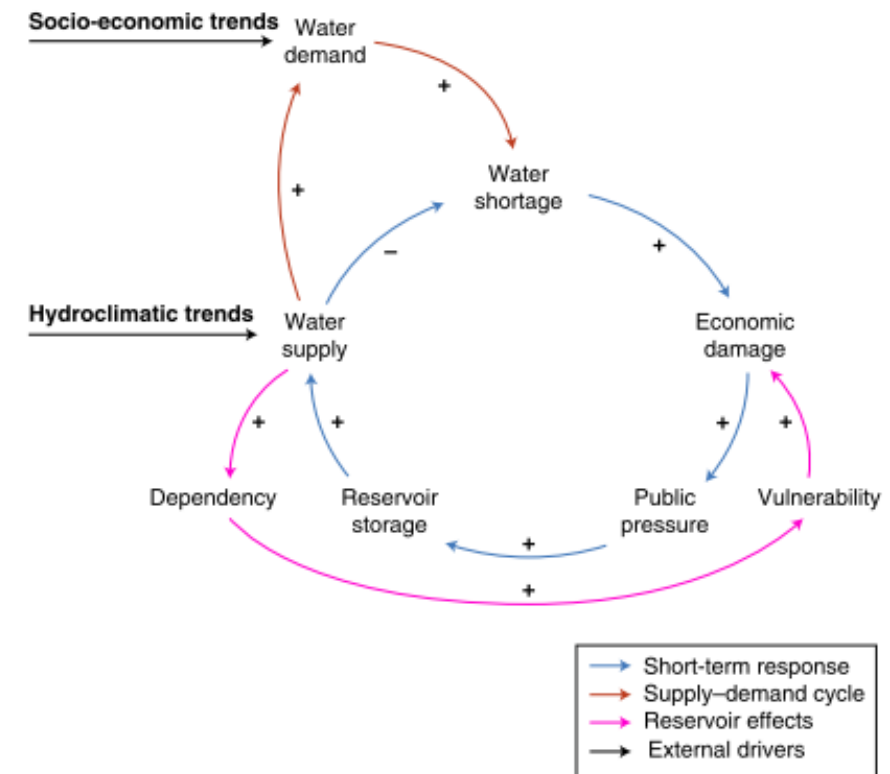
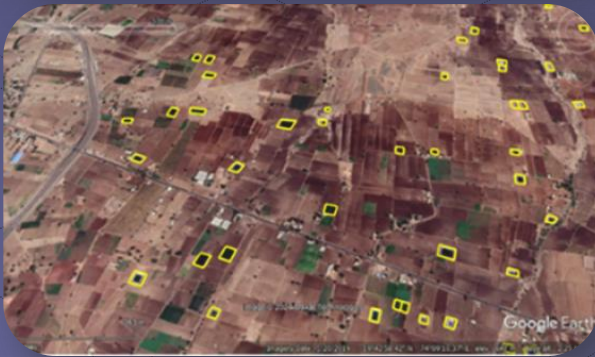


Fig. 2 | Water supply can worsen water shortage. The causal loop diagram shows the positive (+) and negative (-) feedbacks between physical, technical and social processes. Our hypothesis emphasizes the role of internal feedback mechanisms, and the potential emergence of long-term dynamics: supply-demand cycle (red loop) and reservoir effects (pink loop).

Petit exemple de maladaptation



Agricultural Water Management 264 (2022) 107385

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Agricultural Water Management

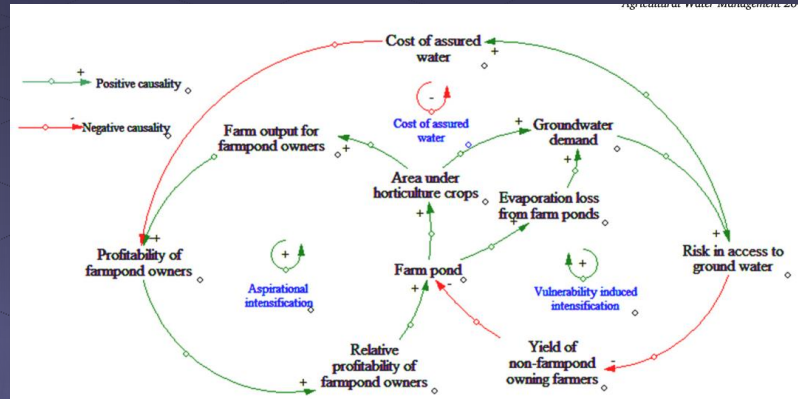
journal homepage: www.elsevier.com/locate/agwat

How can resource-level thresholds guide sustainable intensification of agriculture at farm level? A system dynamics study of farm-pond based intensification

Pooja Prasad ^{a,b,*}, Om P. Damani ^{a,c}, Milind Sohoni ^{a,c}

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^b Land and Water Management Department, IHE Delft Institute for Water Education, Delft, The Netherlands
^c Department of Computer Science and Engineering, Indian Institute of Technology Bombay, India

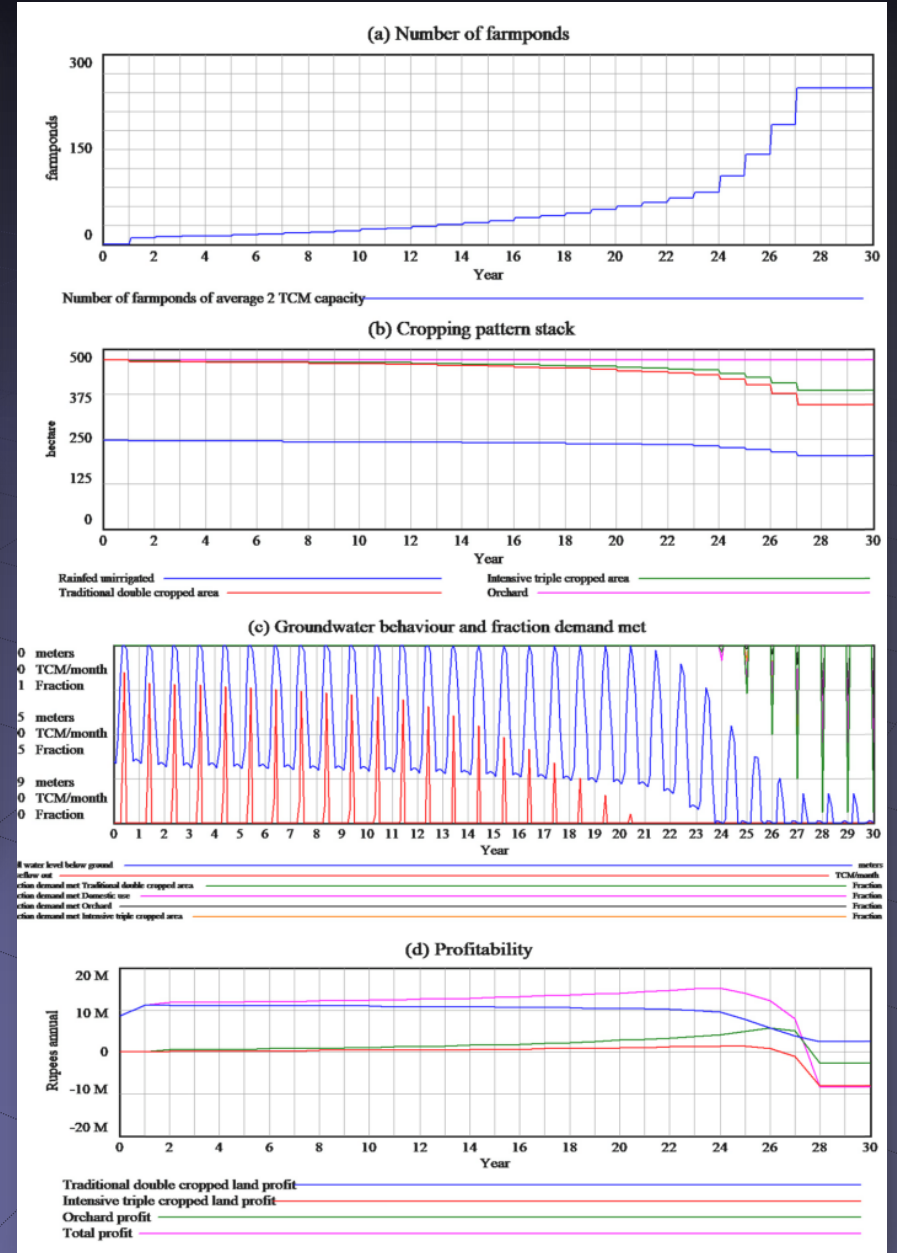
Prasad et al. 2022, Agriculture & Water management



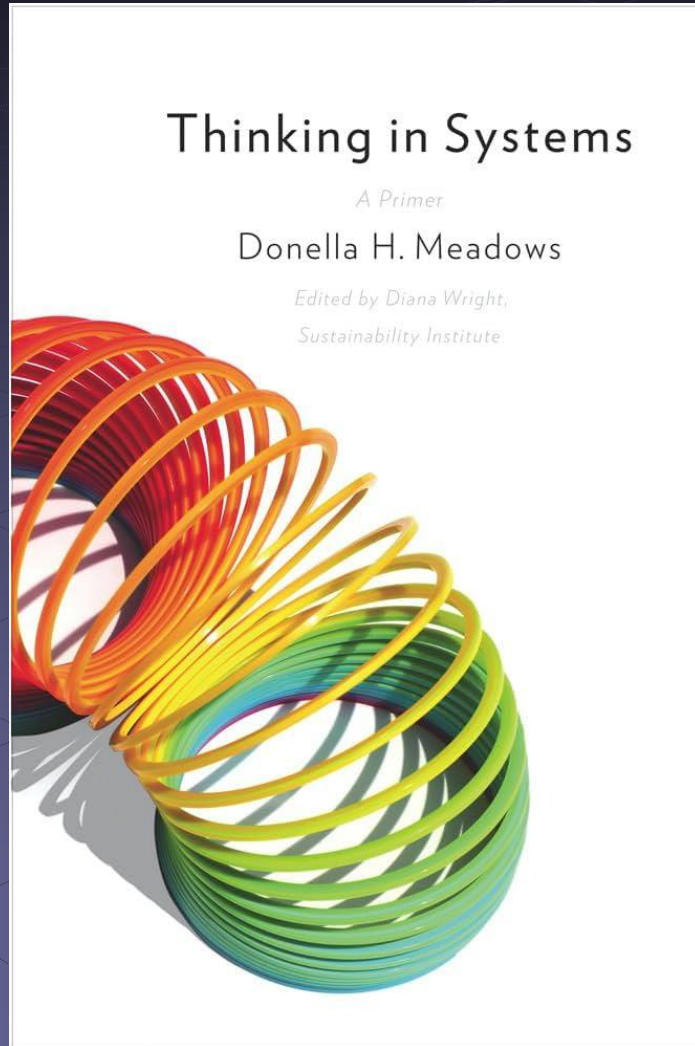
Scénario sans changement climatique

Archétype systémique

« Tragédie des communs »



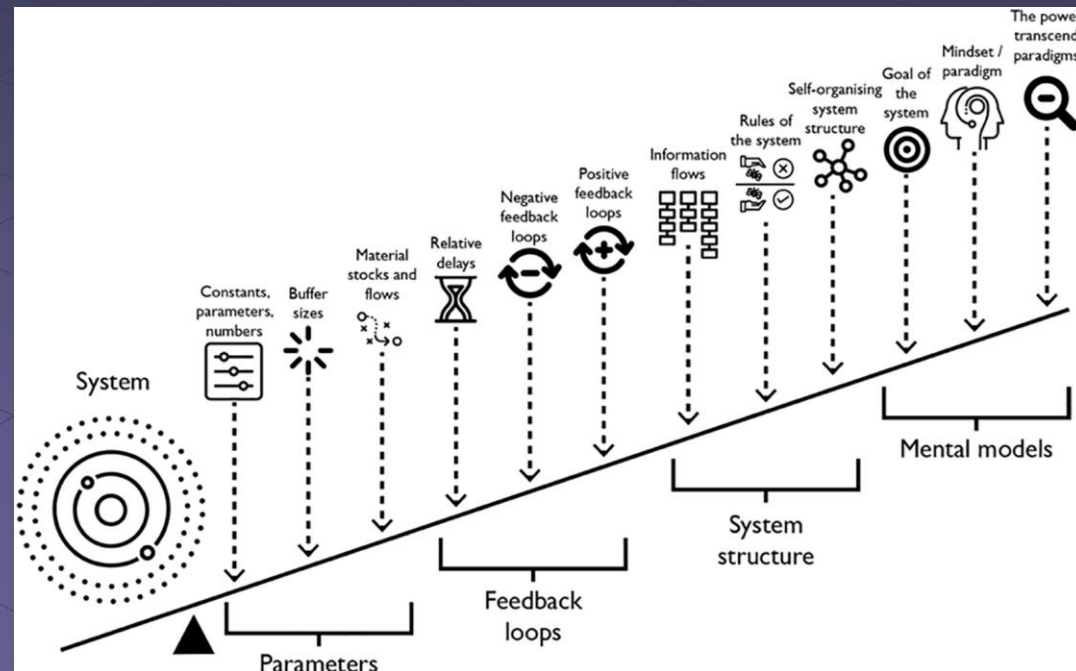
Recommandation de lecture



→ Archétype systémique

→ Leviers systémiques

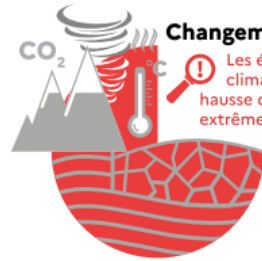
Comprendre
pour bien agir



Recommandation de lecture

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Les 9 limites planétaires*



Changement climatique

Les émissions anthropiques perturbent l'équilibre climatique avec de multiples conséquences : hausse des températures, événements climatiques extrêmes, montée des océans, disparition d'espèces...

Augmentation constante de la concentration de CO₂ dans l'atmosphère : 425 ppm en 2023 contre 280 ppm en 1850.

L'empreinte CO₂ moyenne des Français dépasse de 48 % l'empreinte CO₂ moyenne mondiale.



Érosion de la biodiversité

Destruction d'habitats, exploitation d'espèces, pollution... le déclin de la nature s'accroît, menaçant la santé des écosystèmes et le bien-être humain.

Entre 100 et 1 000 extinctions d'espèces par an sur 1 million d'espèces.

L'indice de risque d'extinction d'espèces a augmenté de 99 % entre 2000 et 2022, contre 36 % dans le reste du monde.



Perturbation des cycles biogéochimiques de l'azote et du phosphore

L'excès d'azote et de phosphore apporté aux cultures (engrais) dégrade les milieux aquatiques : eutrophisation des rivières et anoxie des océans.

150 Mt d'azote rejetées dans la nature (seuils limites : 62-82 Mt) et 22 Mt de phosphore arrivant en mer par les cours d'eau chaque année (limites : 11-100 Mt).

L'excès d'azote atteint la limite planétaire (55 kg/ha). L'excès de phosphore (2 kg/ha) respecte la limite.



Changement d'usage des sols

La déforestation au profit de l'agriculture réduit la capacité des forêts à jouer leur rôle de puits de carbone indispensable à la régulation du climat.

Seulement 62 % de la surface occupée par des forêts avant 1700 est toujours boisée en 2015.

Par ses importations de matières premières, la France exerce une pression forte sur la ressource foncière étrangère.

* La situation décrite est celle connue avant la dernière publication du Stockholm Resilience Centre de septembre 2023.



Utilisation et cycle de l'eau douce

Les prélèvements en eau douce pour les besoins des activités humaines affectent les écosystèmes en perturbant le cycle de l'eau.

Eau bleue : 2 600 km³/an prélevés (seuils limites : 4 000-6 000 km³/an)
Eau verte : anomalie d'humidité pour 18 % des sols (limite : 10 %)

0,2 % des prélèvements nets mondiaux annuels pour l'eau bleue, avec localement des tensions saisonnières.

Acidification des océans

La dissolution de CO₂ dans l'océan réduit le pH de l'eau de mer, entraînant une diminution des carbonates nécessaires à la formation des coquillages en aragonite.

En 2015, l'état de saturation de l'eau de mer en aragonite est estimé à 84 % du niveau préindustriel.

Appauvrissement de l'ozone stratosphérique

Les substances appauvrissant la couche d'ozone réduisent son rôle protecteur face aux rayons du soleil, nocifs pour la santé humaine et les écosystèmes.

La concentration d'ozone dans la stratosphère est estimée à 285 DU (unités Dobson) en 2015 (limite : 275 DU).

Augmentation des aérosols dans l'atmosphère

Une quantité croissante d'aérosols (petites particules en suspension) émis dans l'atmosphère perturbe le climat et a des effets sur la santé humaine.

Pas de seuil global défini en l'absence de connaissances suffisantes.

Introduction d'entités nouvelles dans la biosphère

La production de produits chimiques et plastiques augmente si vite que la capacité d'évaluation des risques pour l'homme et la biosphère est dépassée.

Produits chimiques : production multipliée par 50 depuis 1950. Produits plastiques : + 79 % entre 2000 et 2015

Limite	
■ dépassée (risque élevé)	
■ forte incertitude (risque croissant)	
■ non dépassée	
■ non quantifiée	

Sélection BD grand public

