Introduction au concept de Limites Planétaires

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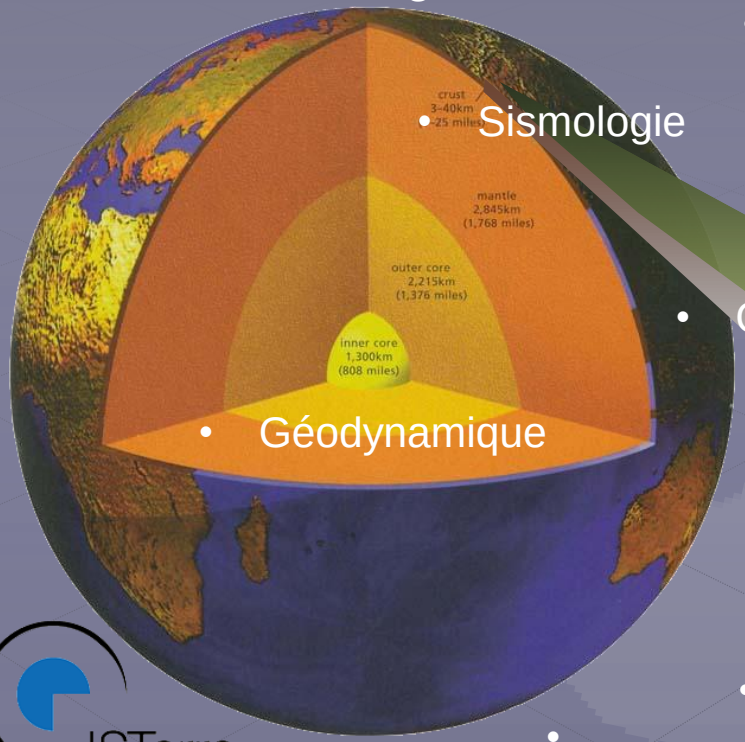
École d'Automne IA²-2025 − IA et limites planétaires - Aussois, 13−17 octobre 2025

Mon domaine de recherche et d'enseignement

Géosciences

Terre interne

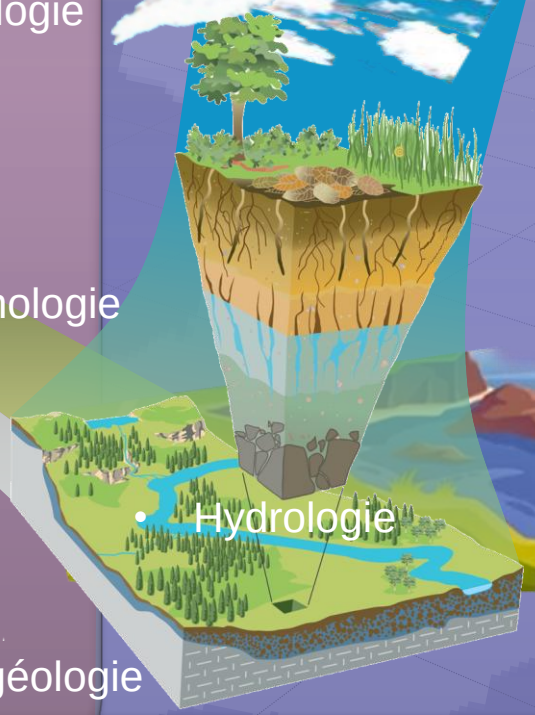
Géologie



- Sismologie
- Géodynamique
- …

Terre externe

- Climatologie
- Glaciologie
- Géomorphologie
- Hydrologie
- Hydrogéologie
- Océanographie

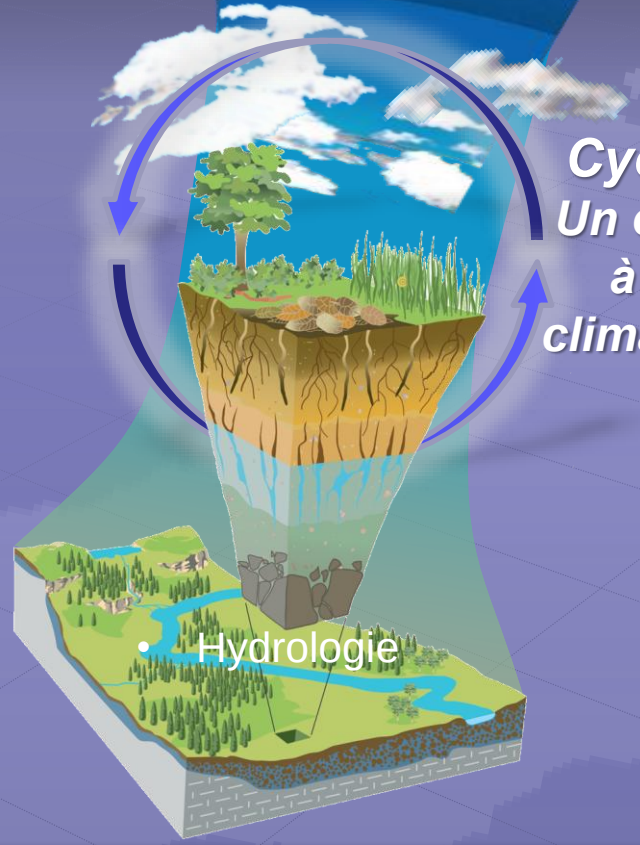


ISTerre

IGE
Institut des géosciences de l'environnement

Mon domaine de recherche et d'enseignement

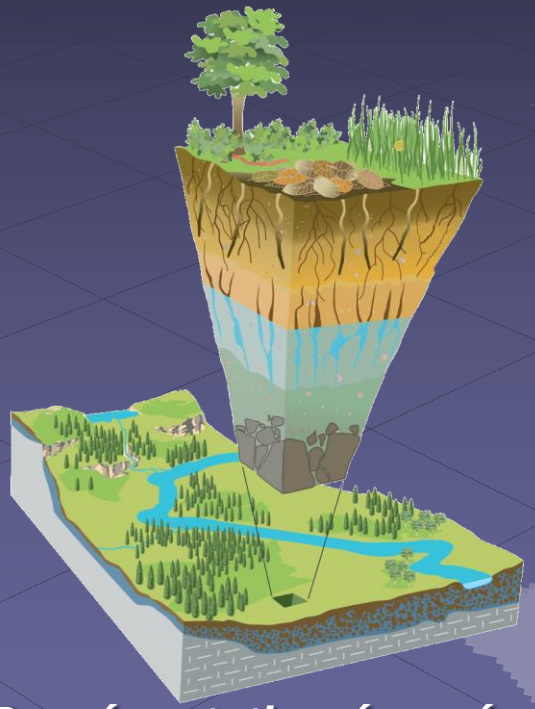
- Climatologie



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

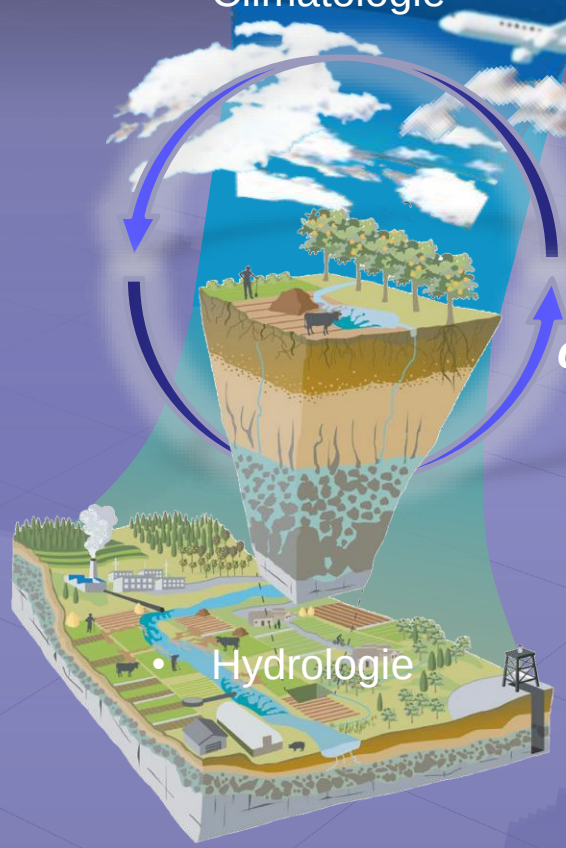
- Hydrologie

Mon domaine de recherche et d'enseignement



Représentation érronée
mais encore prégnante de l'hydrologie

- Climatologie



- Hydrologie

Cycle de l'eau
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climat-hydrologie
Société

Mon domaine de recherche et d'enseignement

INITIATIVE INDIVIDUELLE

Mieux comprendre les inter-relations entre hydrologie et société

UPPSALA UNIVERSITET
2023-24

INITIATIVES COLLECTIVES

Questionner mes pratiques de recherches

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

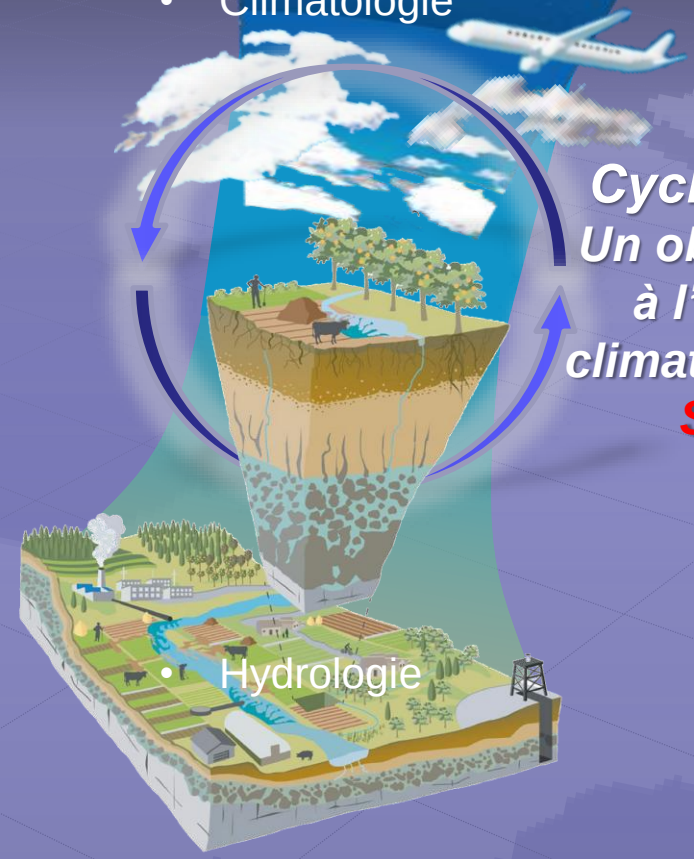
Réorienter une partie de mes enseignements sur les enjeux socio-environnementaux

UGA DESIGN FACTORY

ANTHROPOCÈNE ET LIMITES PLANÉTAIRES

GREEN UNIVERSITY

- Climatologie



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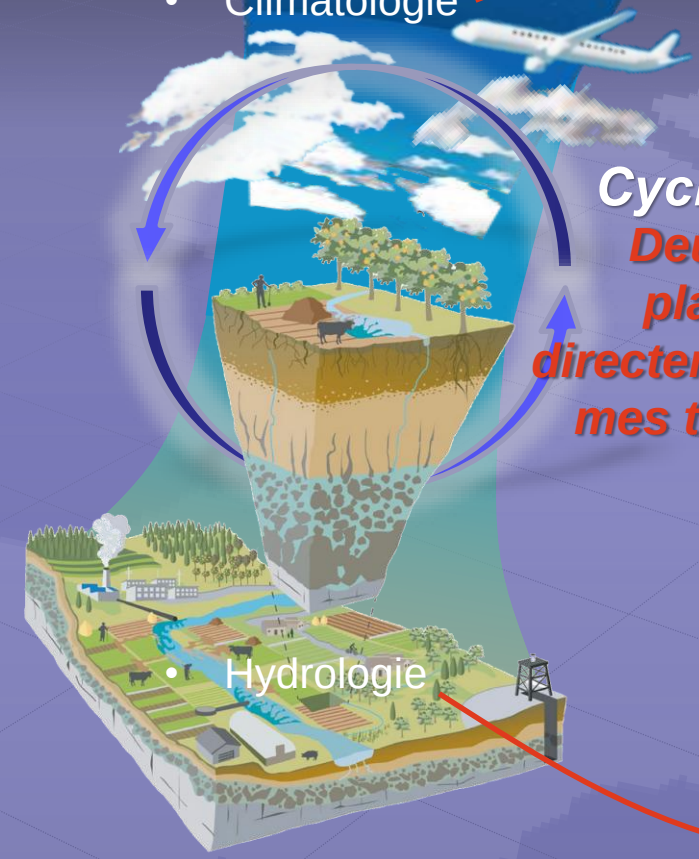
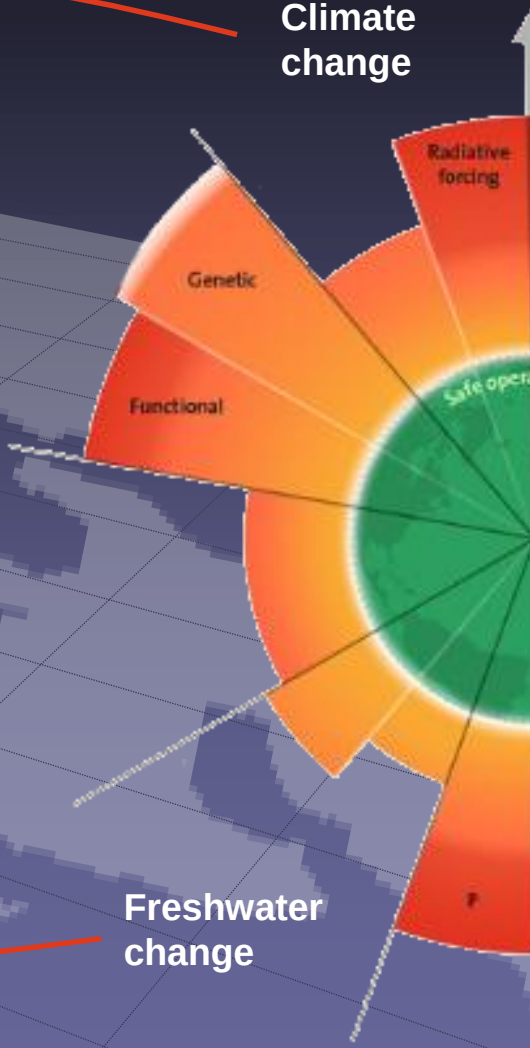


- Hydrologie

Cycle de l'eau
Deux limites planétaires directement reliées à mes thématiques

Climate change



Freshwater change

Mes limites sur les limites

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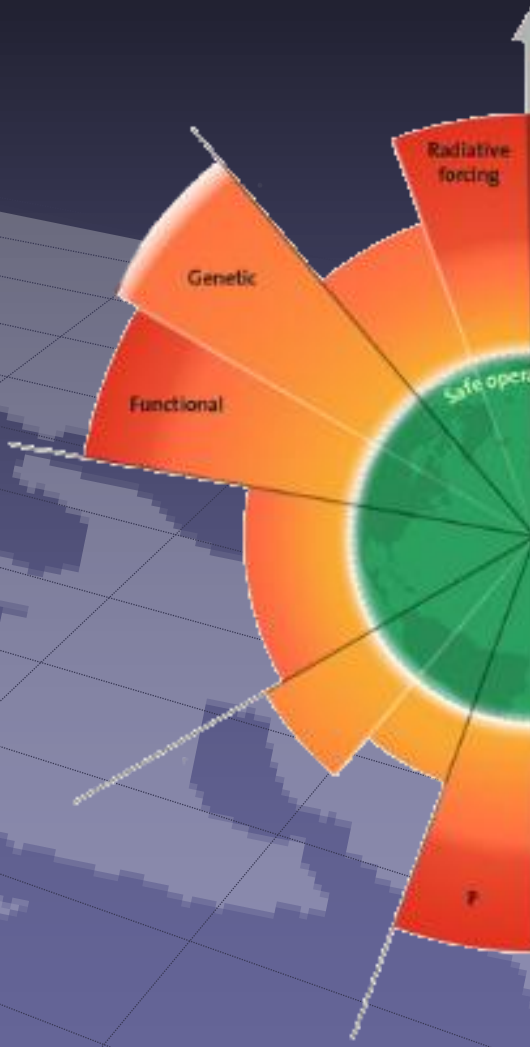
UGA DESIGN FACTORY

ANTHROPOCÈNE ET LIMITES PLANÉTAIRES

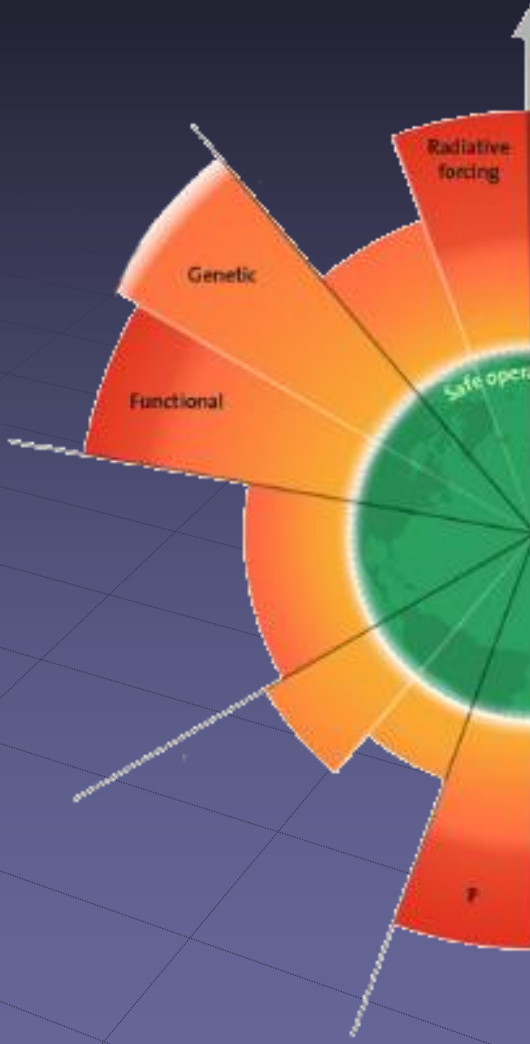
GREEN UNIVERSITY

- 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



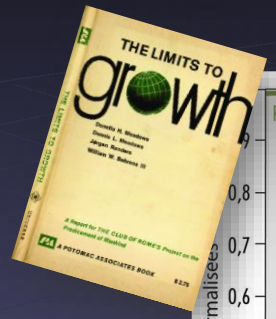
Objectifs de la présentation

- Définir le concept de Limites Planétaires
- Décrire la science mobilisée dans le concept
- Présenter les critiques du concept
- Discuter du cadre de son utilisation
- Ouvrir vers la démarche systémique

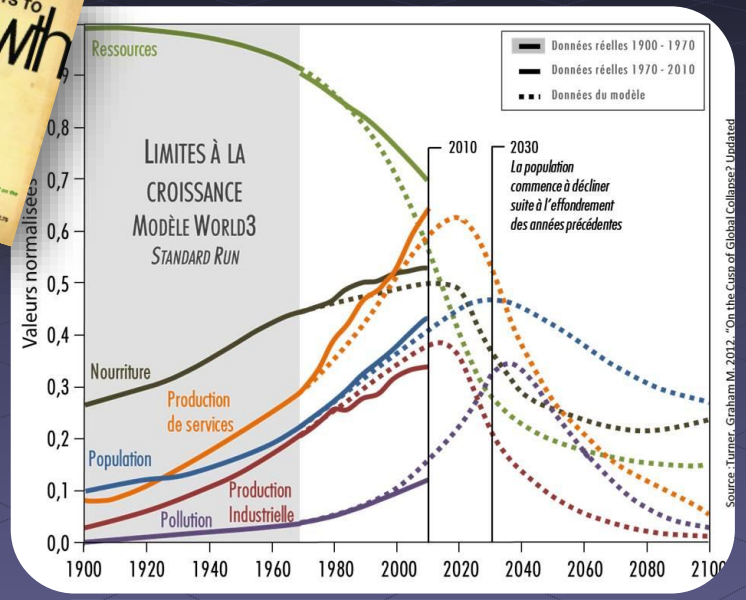


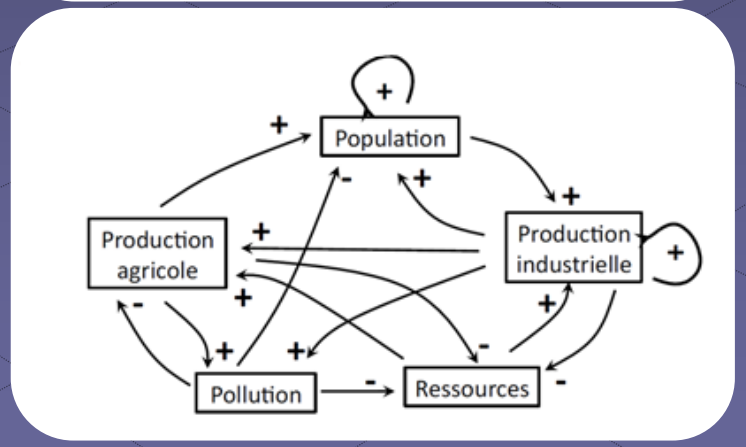
Définition des limites planétaires

Ce qu'elles ne sont pas…



Limites à la croissance





Meadows et al. 1972 (+ update)

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

Définition des limites planétaires

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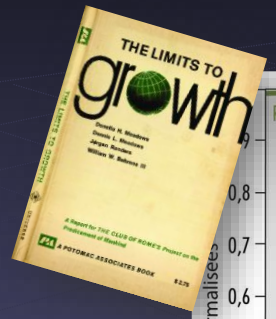

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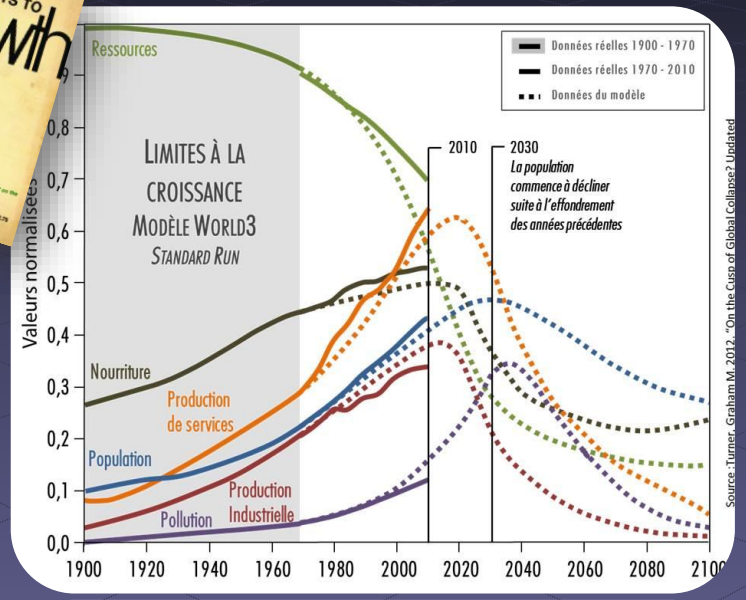
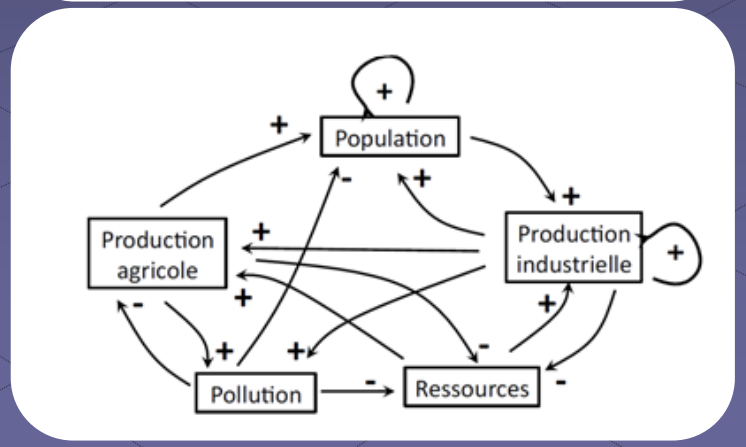


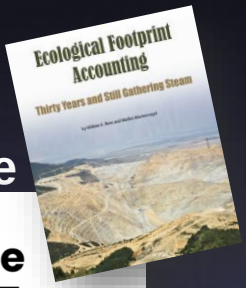


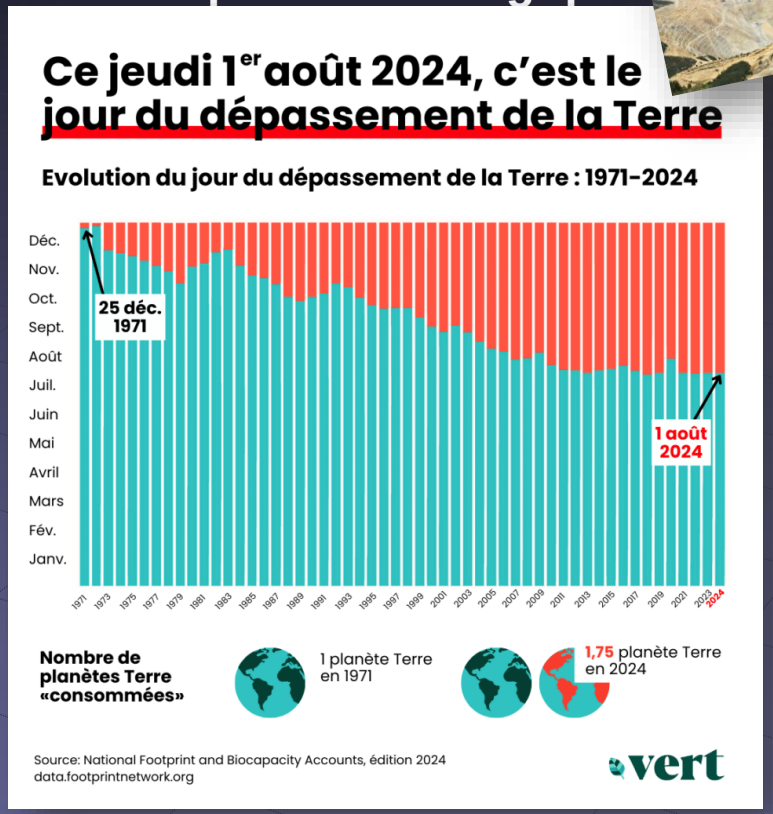
Meadows et al. 1972 (+ update)

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 regénérer les ressources et absorber les pollutions.

Empreinte écologique



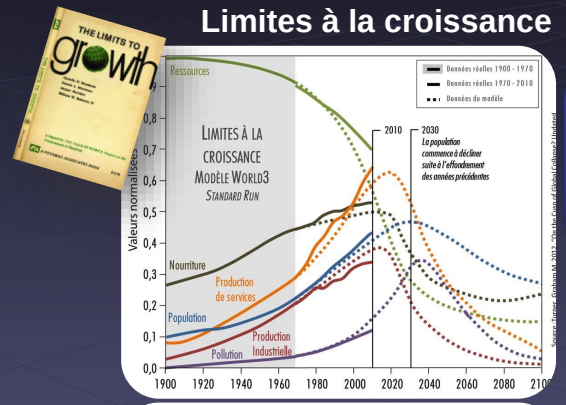


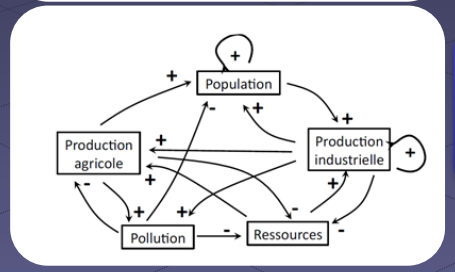
Rees, 1992, Wackernagel and Rees, 1996

Définition des limites planétaires

Ce qu'elles ne sont pas…

Limites à la croissance





Meadows et al. 1972 (+ update)

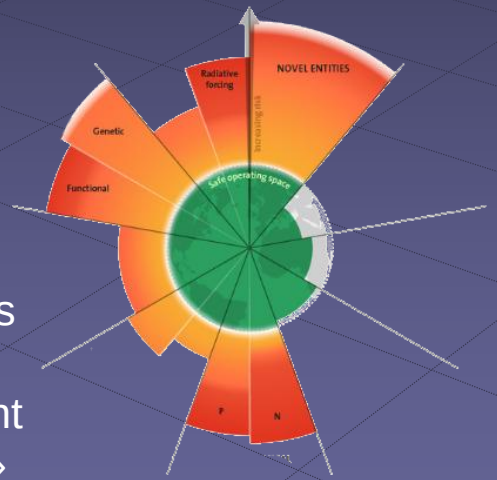
Facteurs socio-économiques

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



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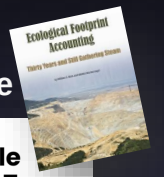
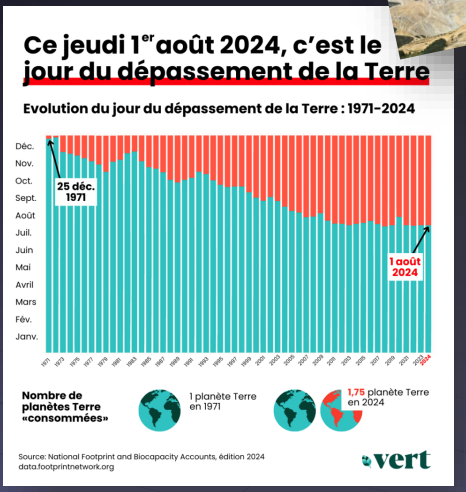




Rees, 1992, Wackernagel and Rees, 1996

Indicateurs Globaux

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

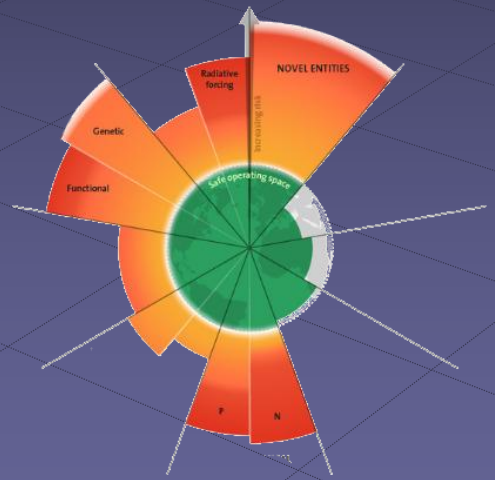
Système Terre

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)

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



Système Terre

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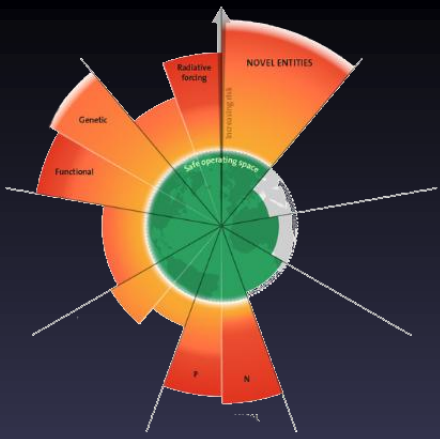

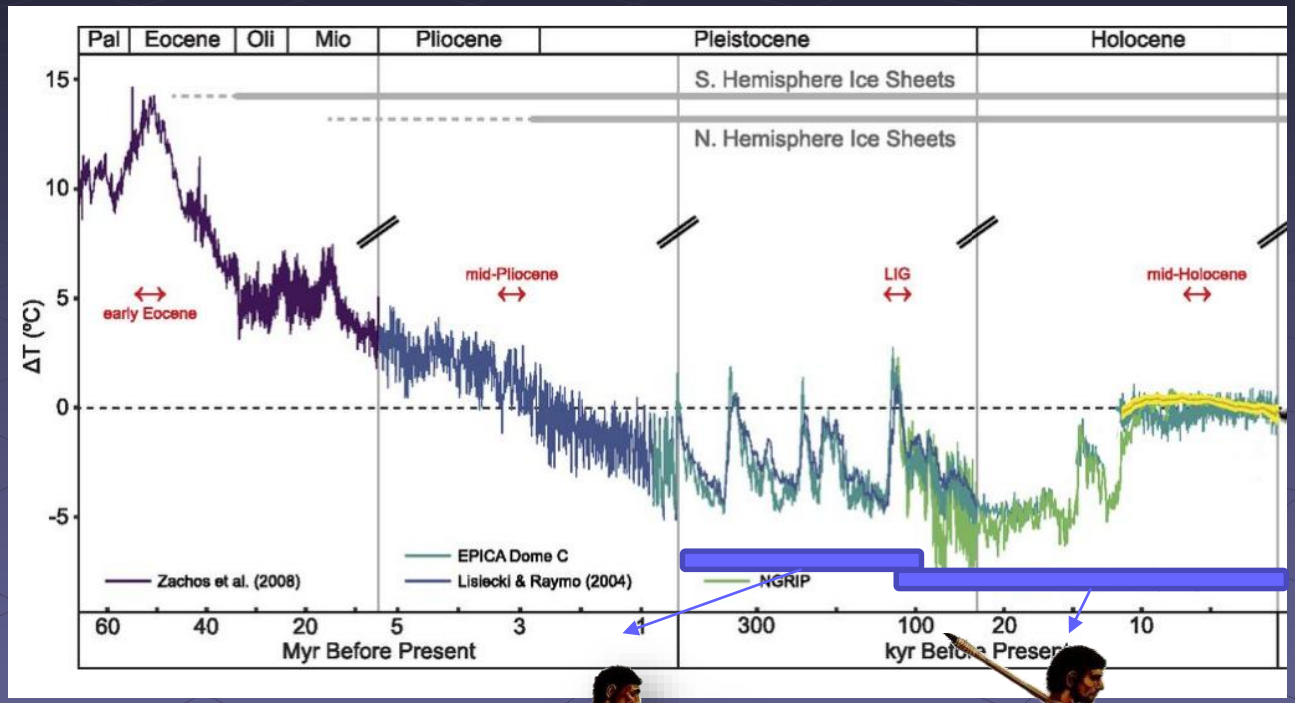

Homo Erectus

Homo Sapiens

Définition des limites planétaires

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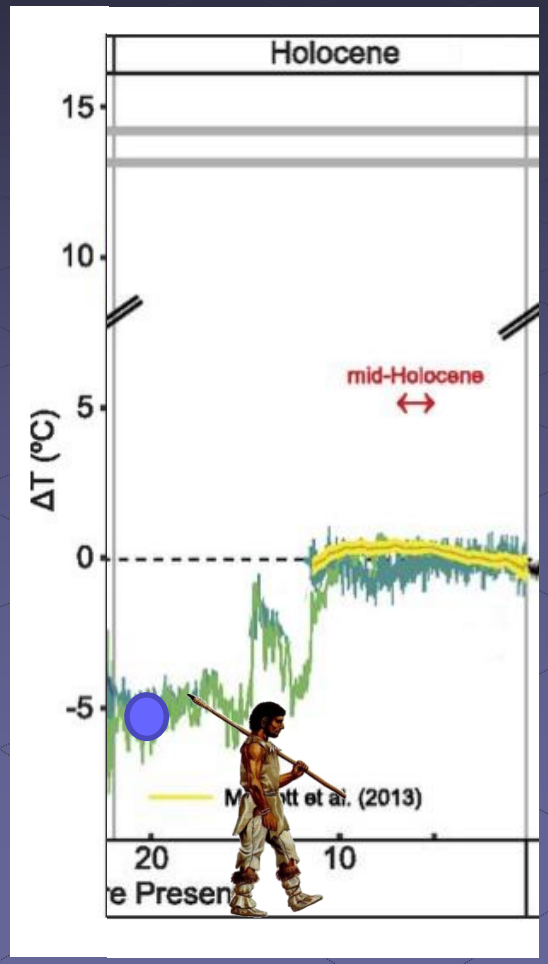

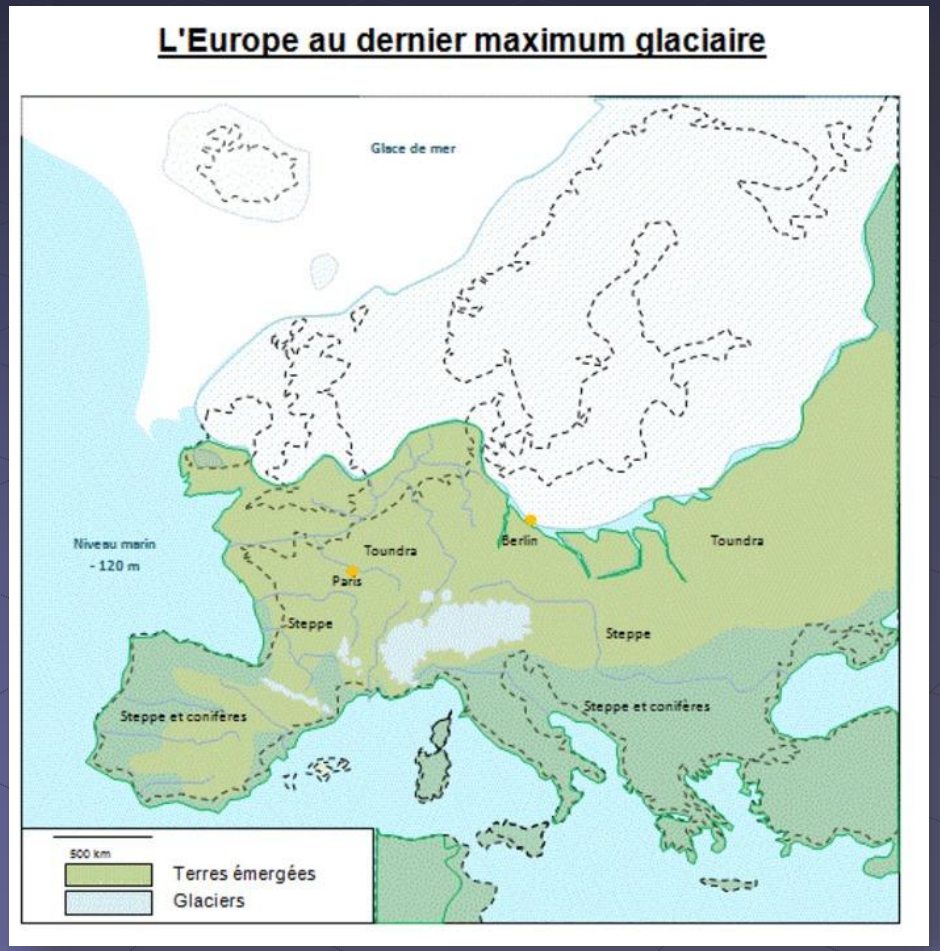

La température de la planète était plus froide qu'aujourd'hui de 5°C

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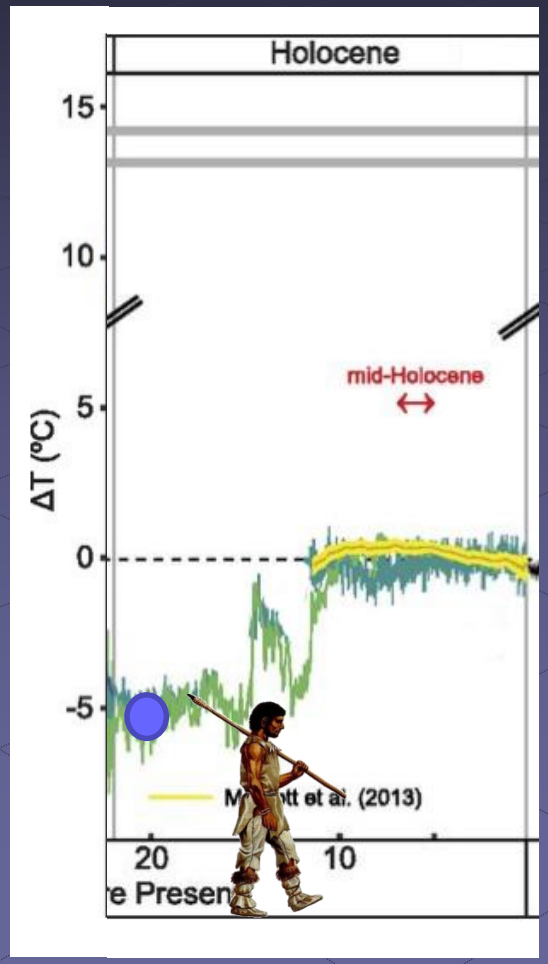

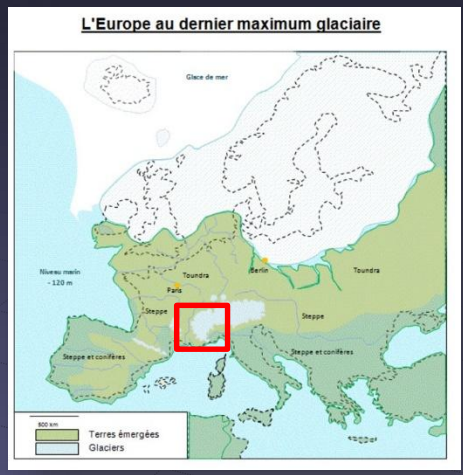

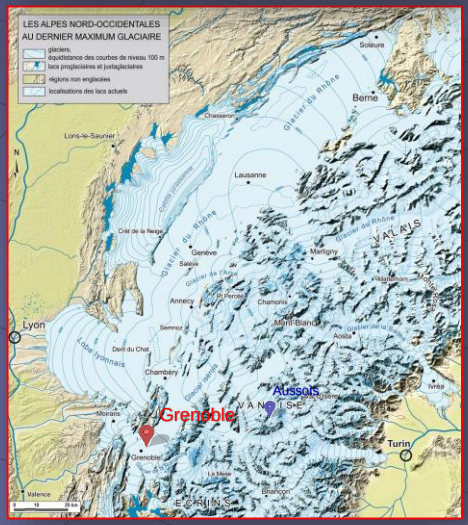

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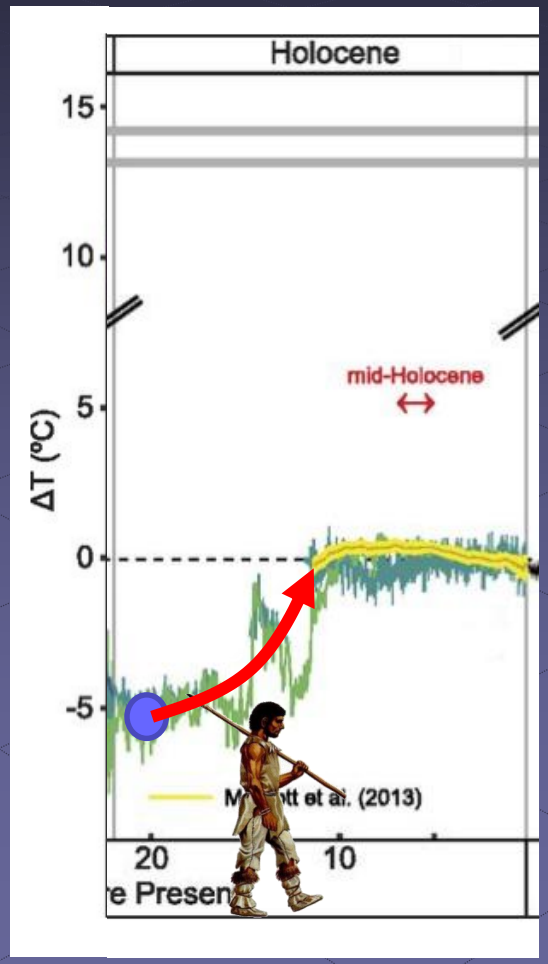

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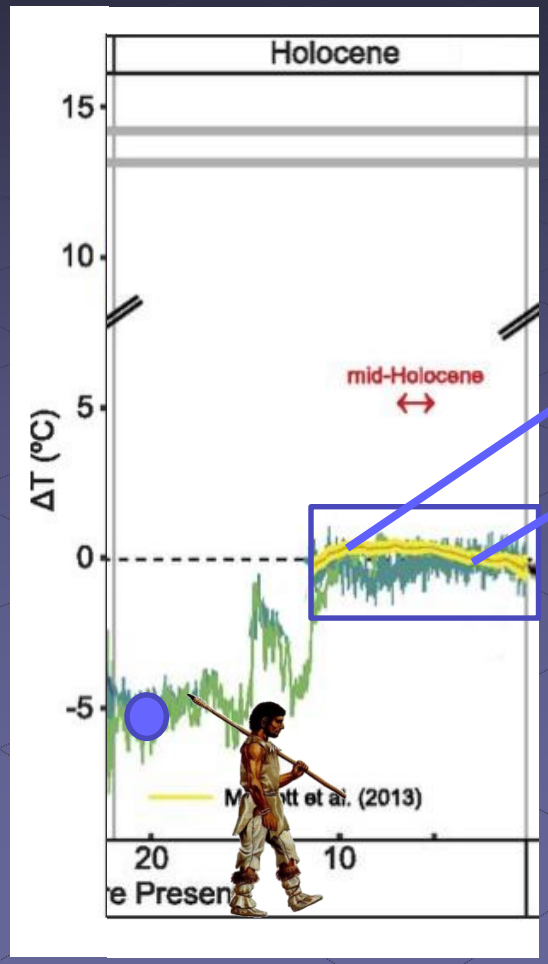

- Début de l'agriculture
- Développement des grandes civilisations sur l'ensemble des continents.
- Des impacts humains connus (modifications d'occupation des sols, des feux, extinction d'espèces) mais rien de global jusqu'ici.

« 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

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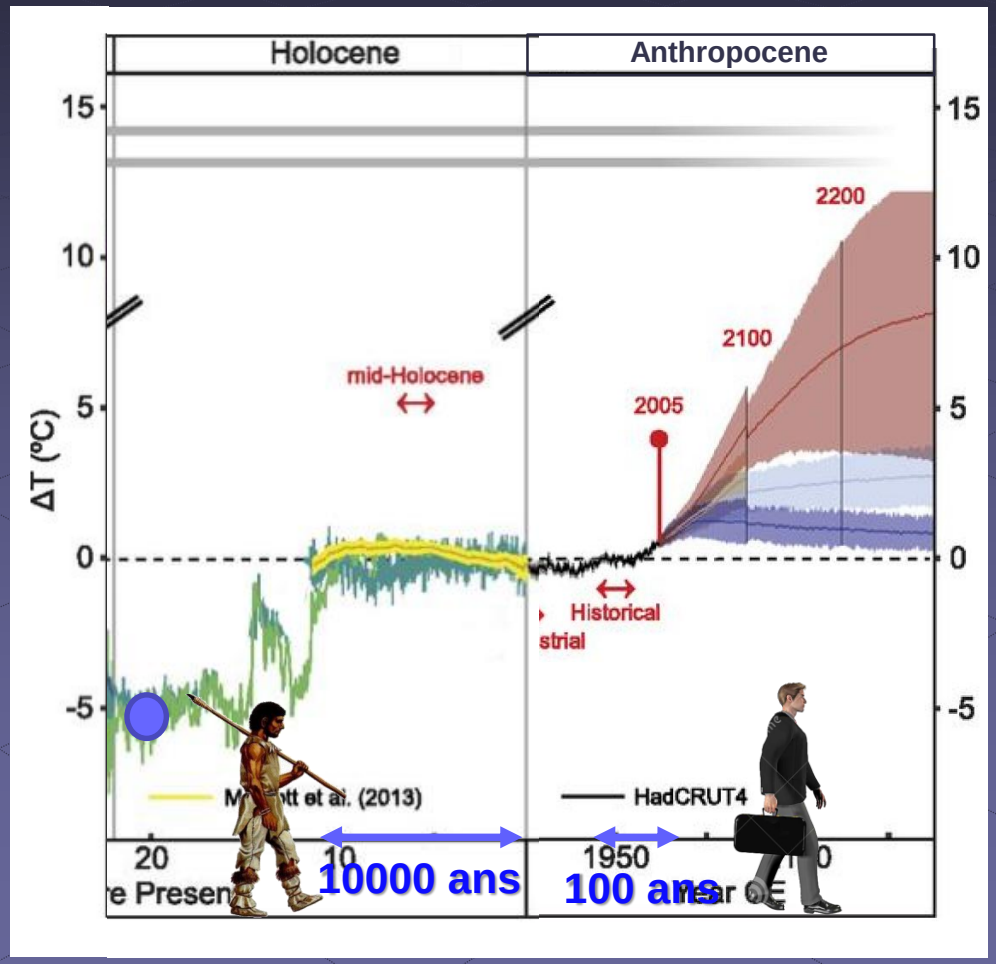


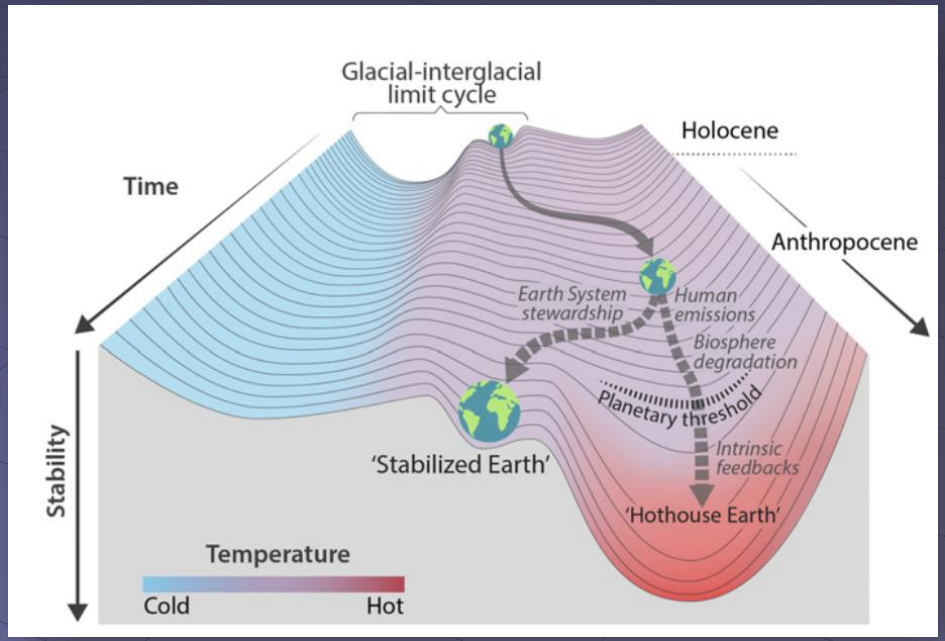
Anthropogenic Climate Change

+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

"Environmental changes that would be deleterious or even catastrophic for human well-being" Rockström et al. 2009a



Steffen et al. 2018, PNAS

Définition des limites planétaires

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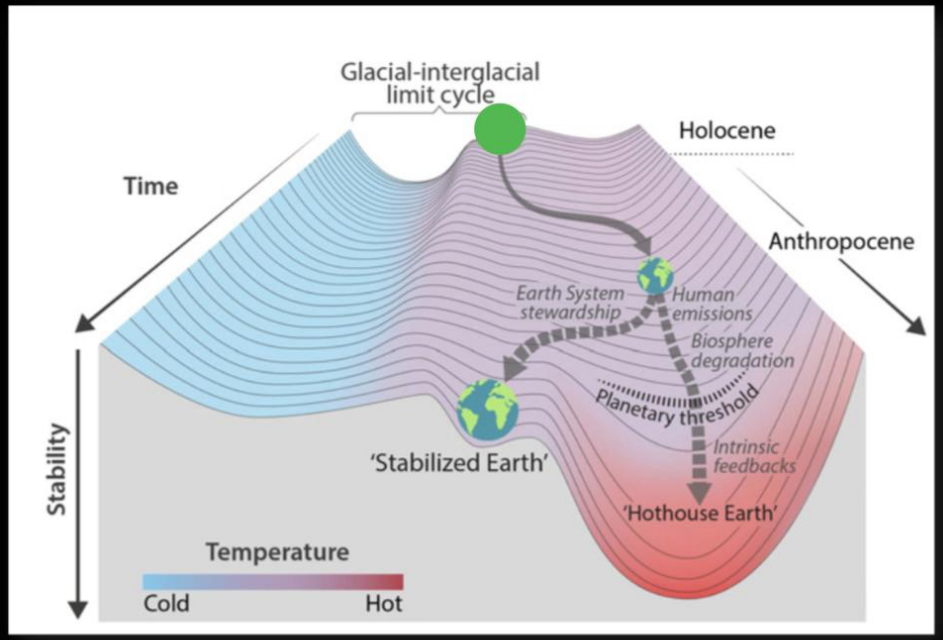
On oscille tranquille dans l'Holocène



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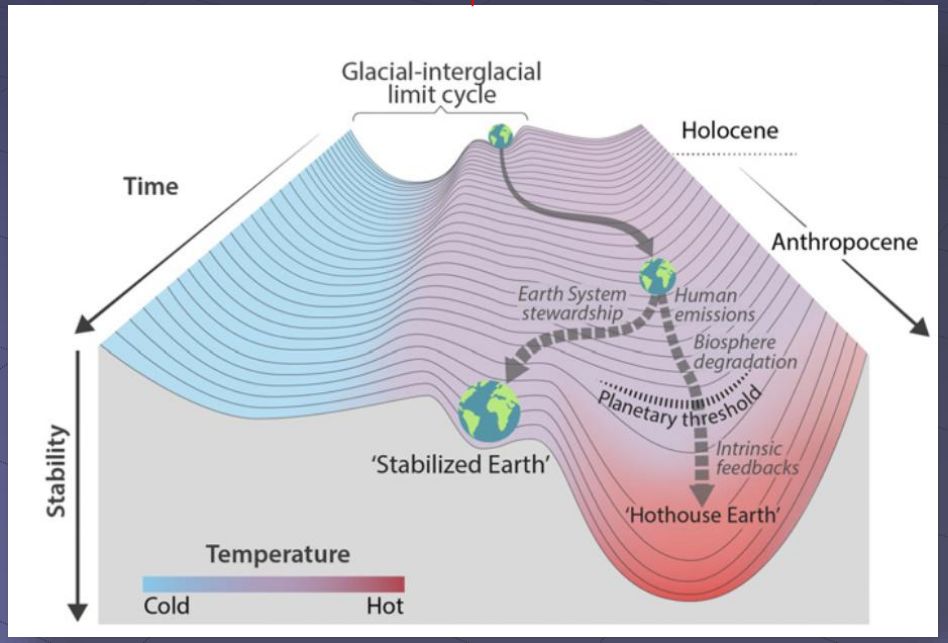
(Rockström et al. 2009a,b; Steffen et al. 2015; Richardson et al. 2023)

Stabilité du système Terre: comparable à un système complexe de plusieurs balançoires
!Traduction personnelle très simplifiée!

Climate Change



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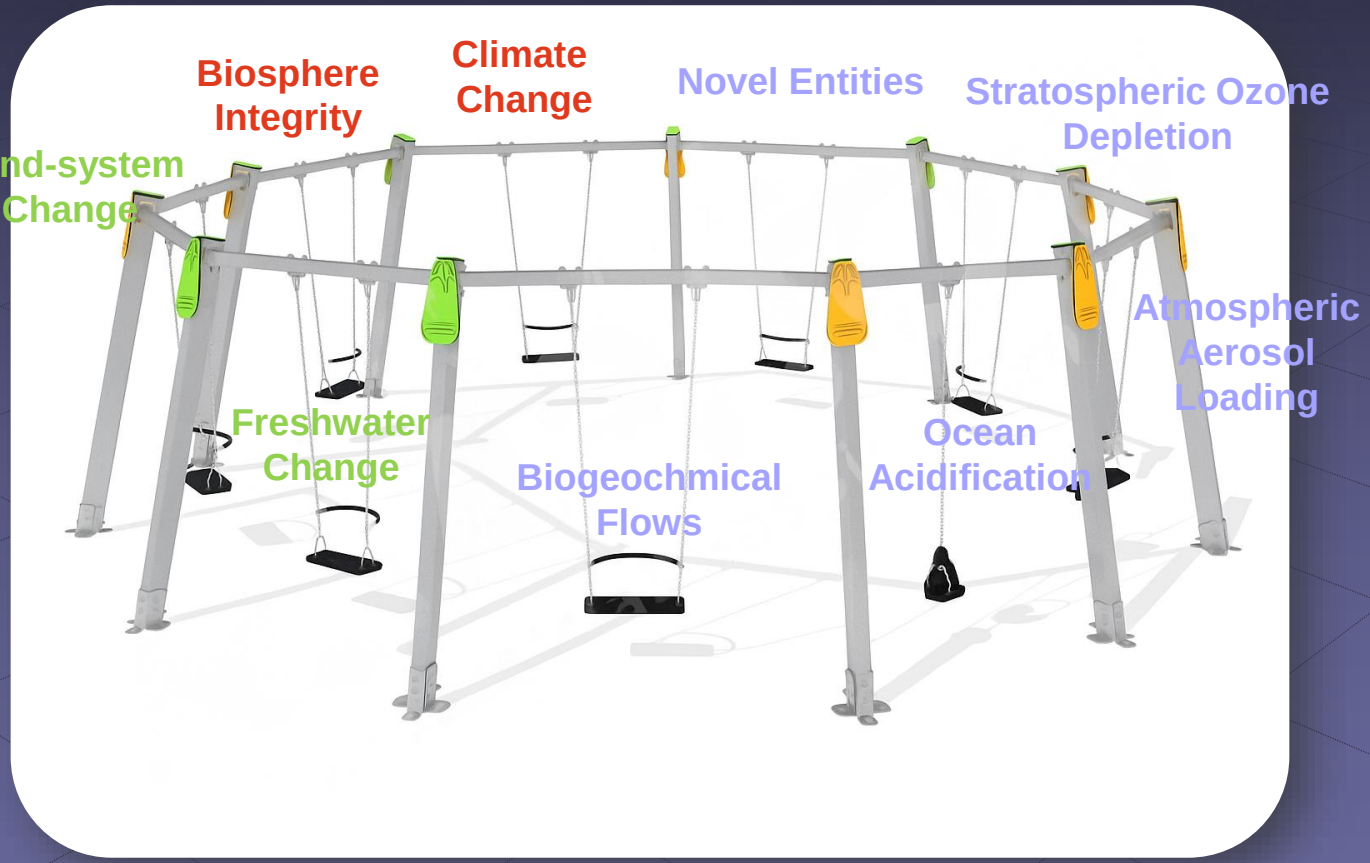

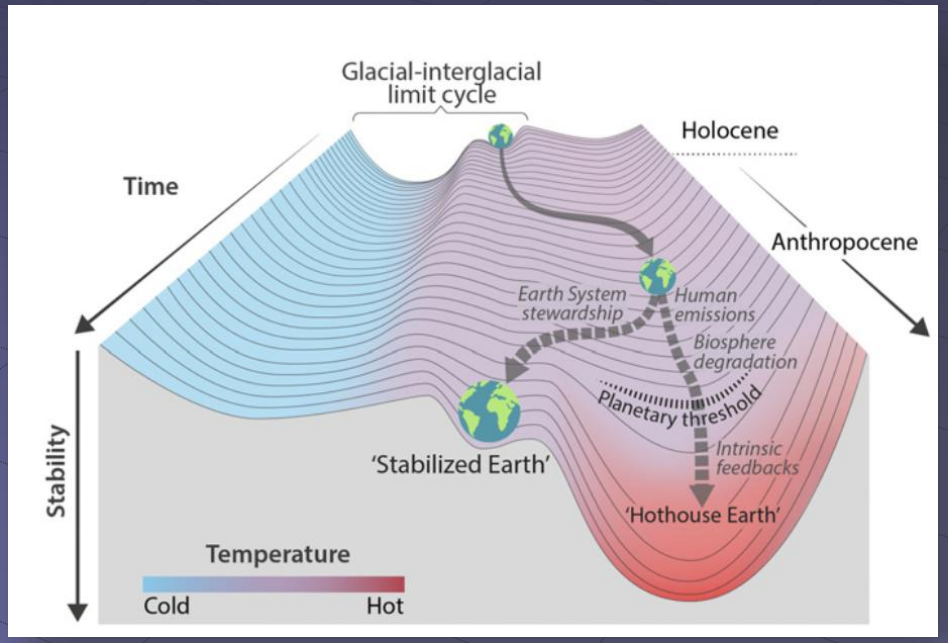

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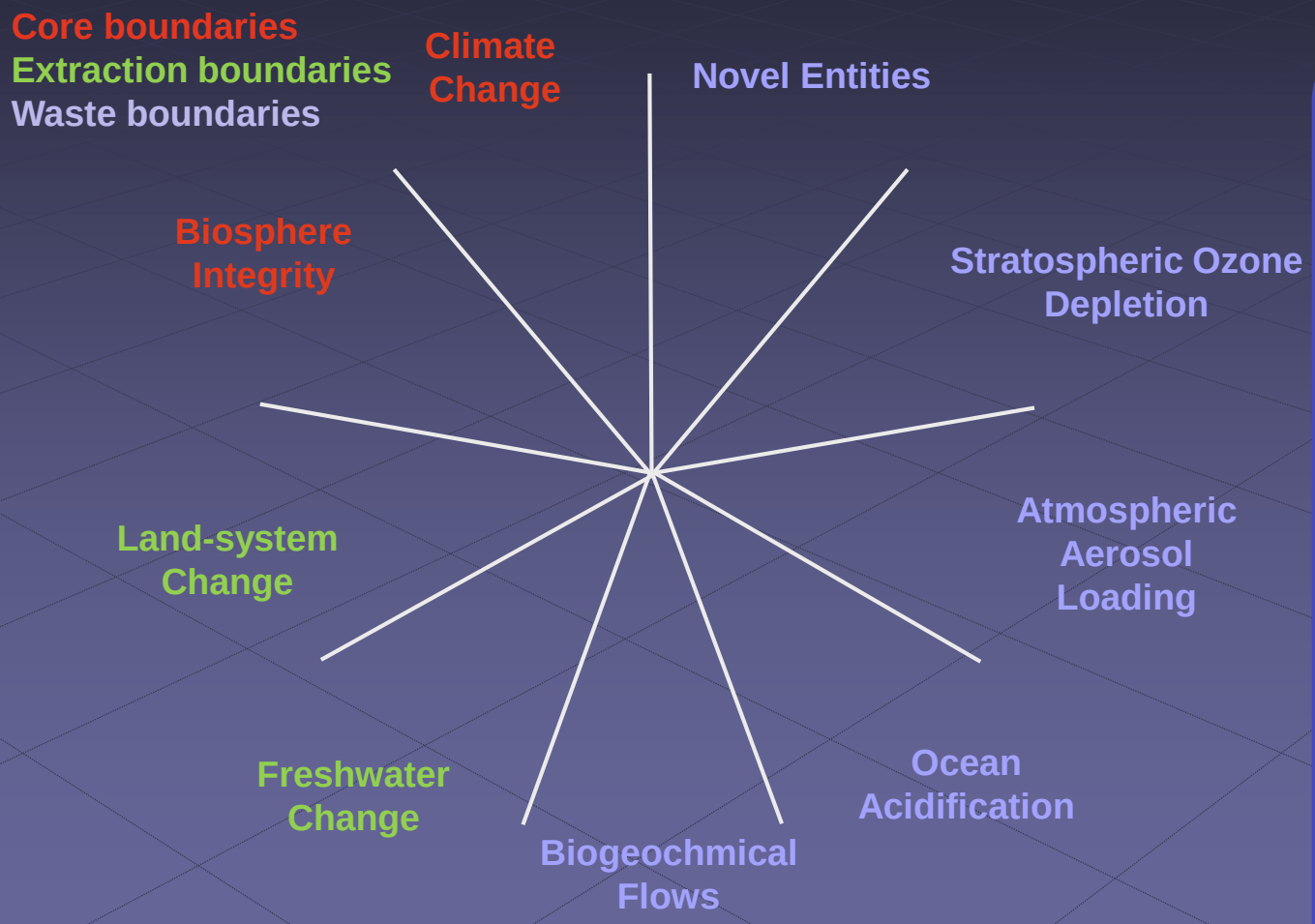

Cadre d'analyse

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

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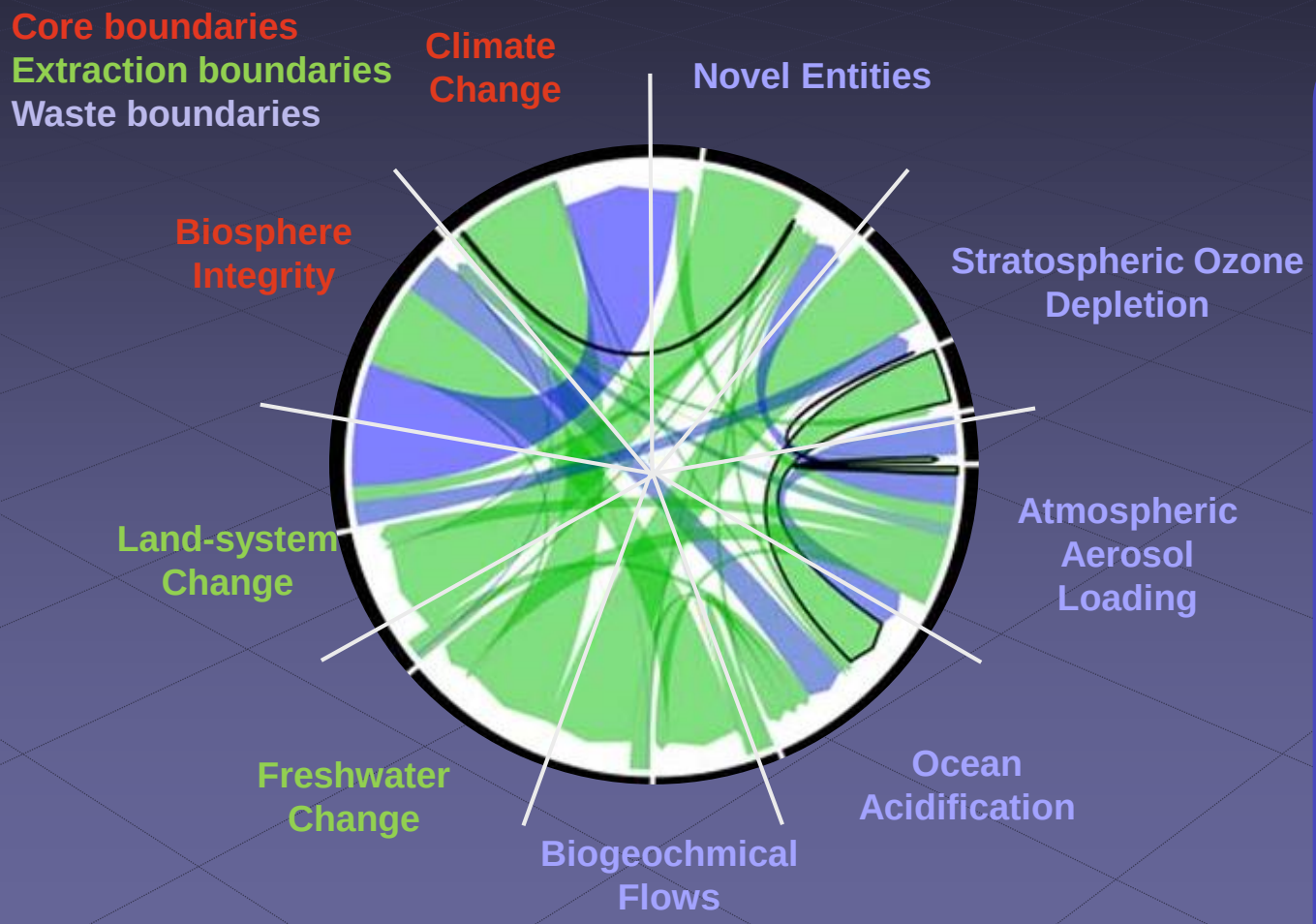

Lade et al. 2020

Cadre d'analyse

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

Définition des limites planétaires

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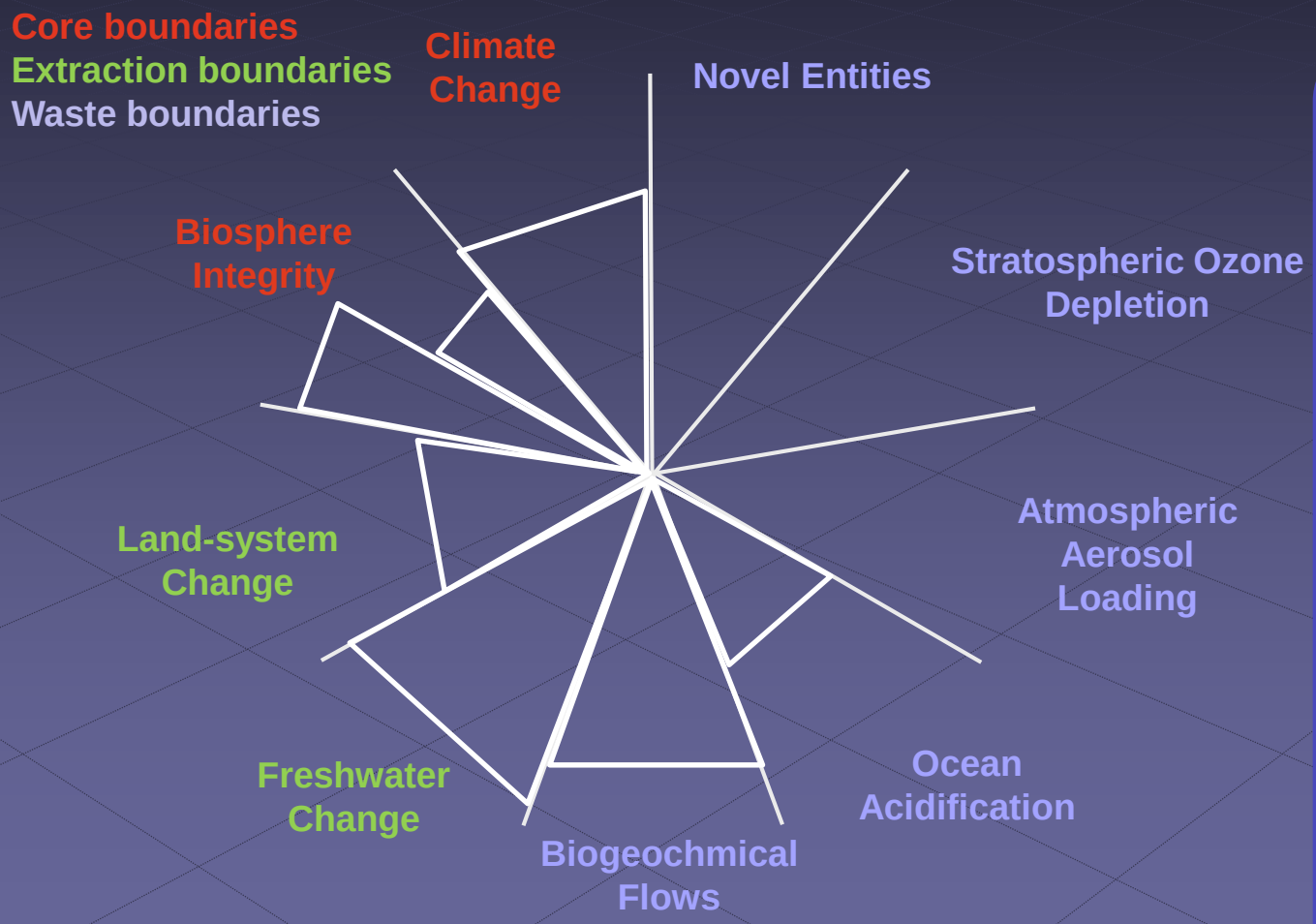

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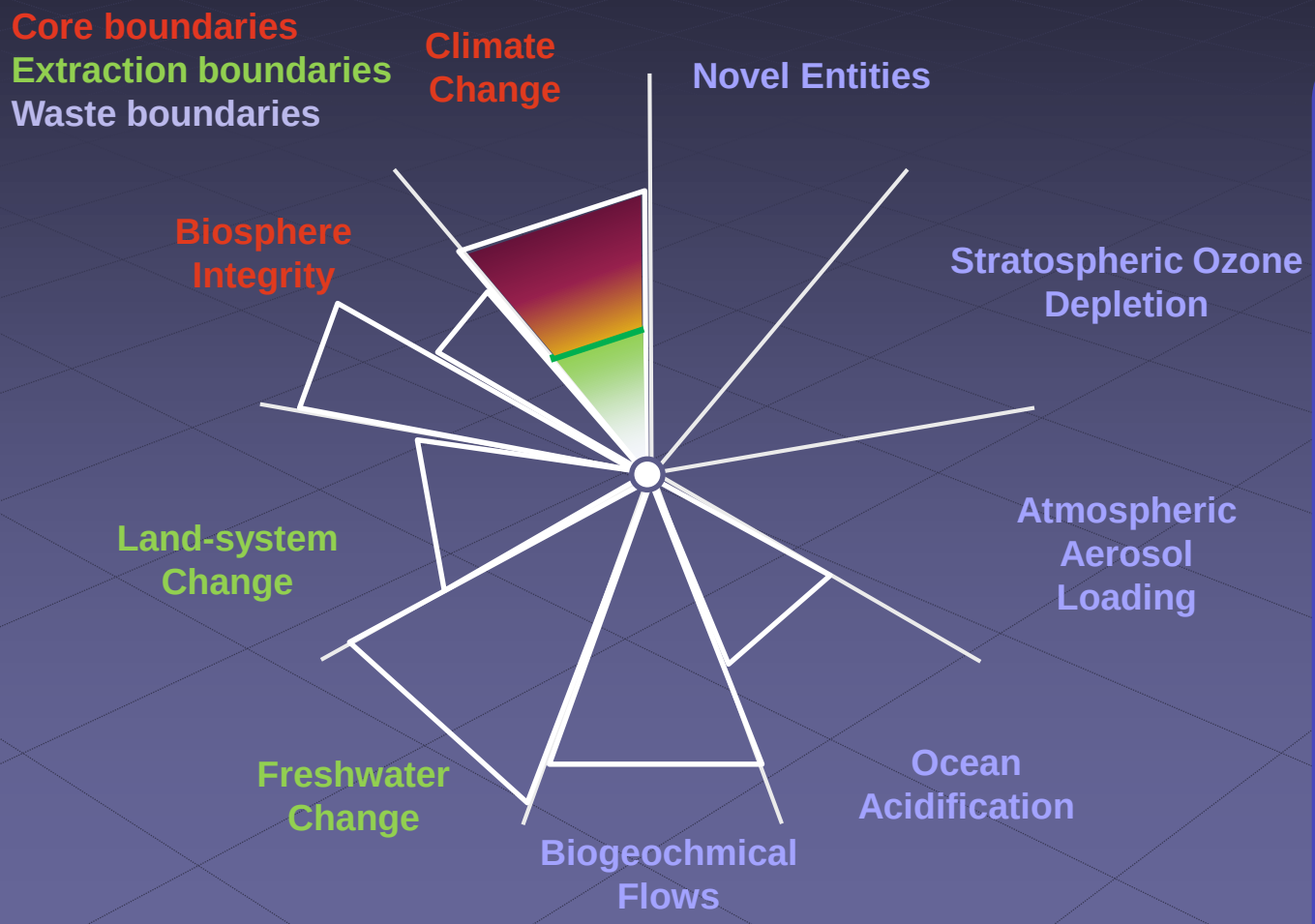

Lade et al. 2020

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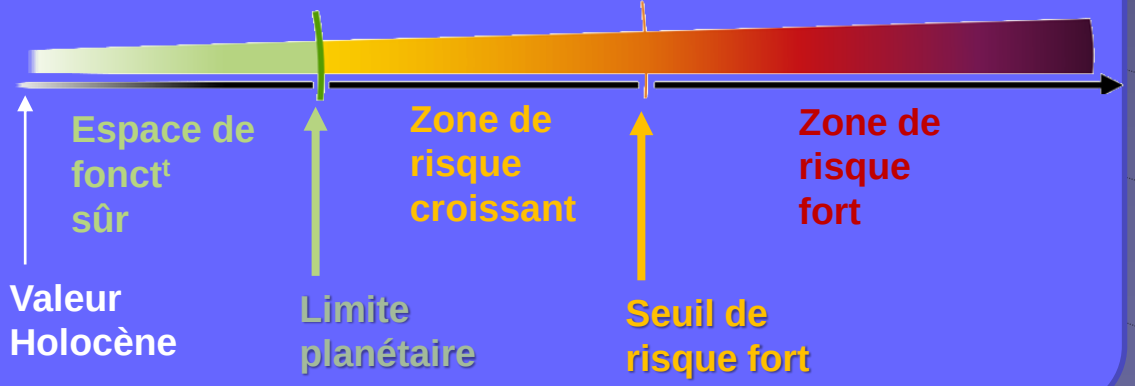
- **Zones et seuils pour chaque processus**



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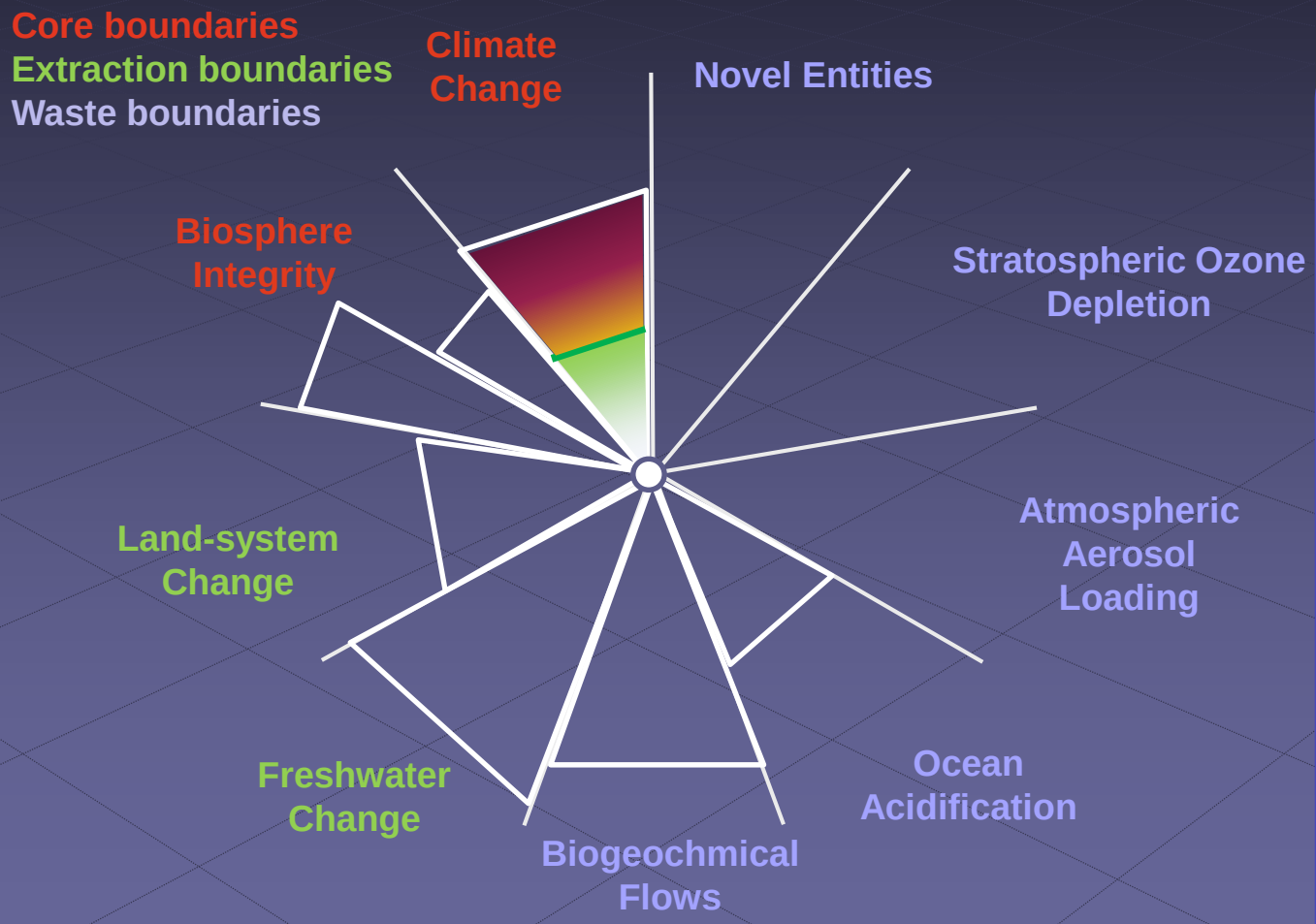

Lade et al. 2020

Cadre d'analyse

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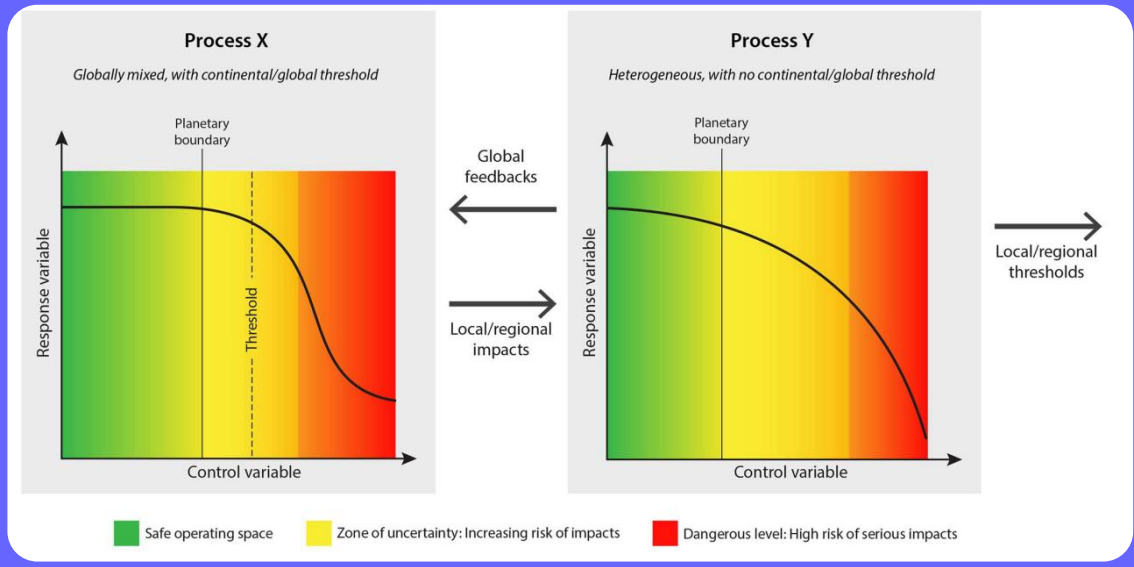

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!Traduction personnelle très simplifiée!

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- les seuils sont les valeurs critiques
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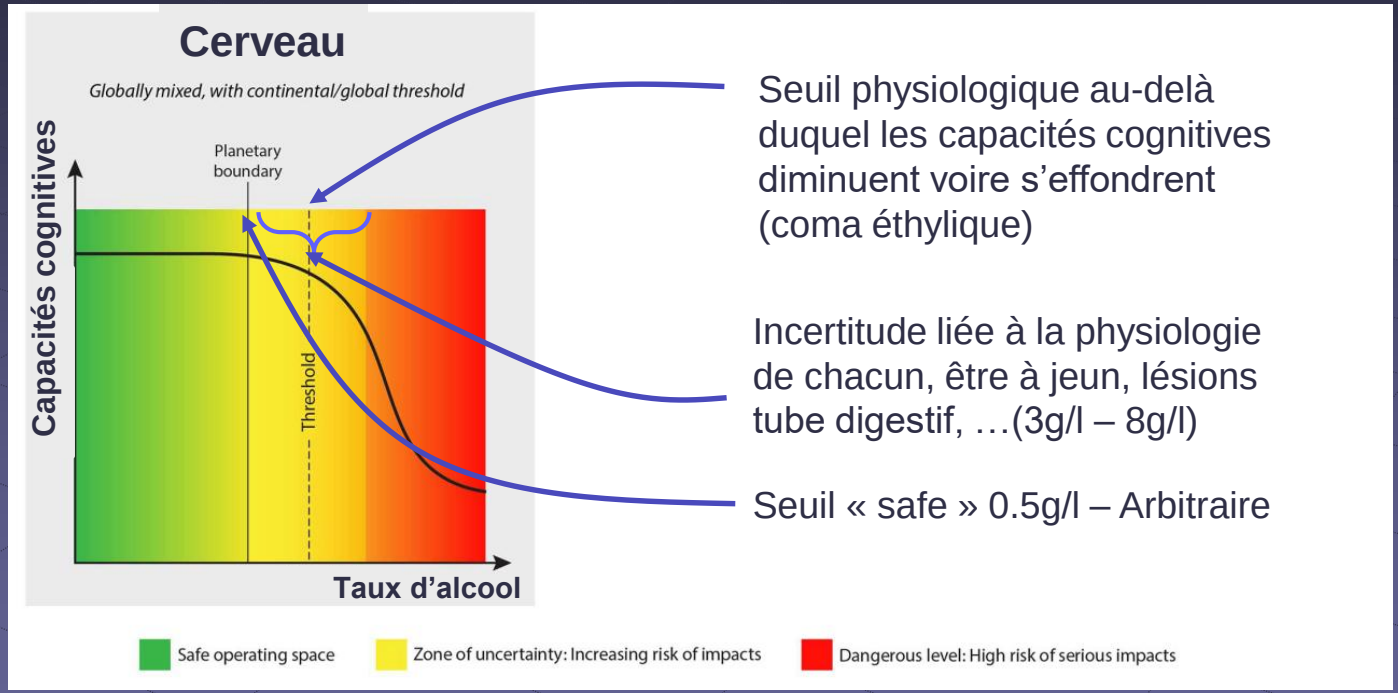

Variable à seuil

Définition des limites planétaires

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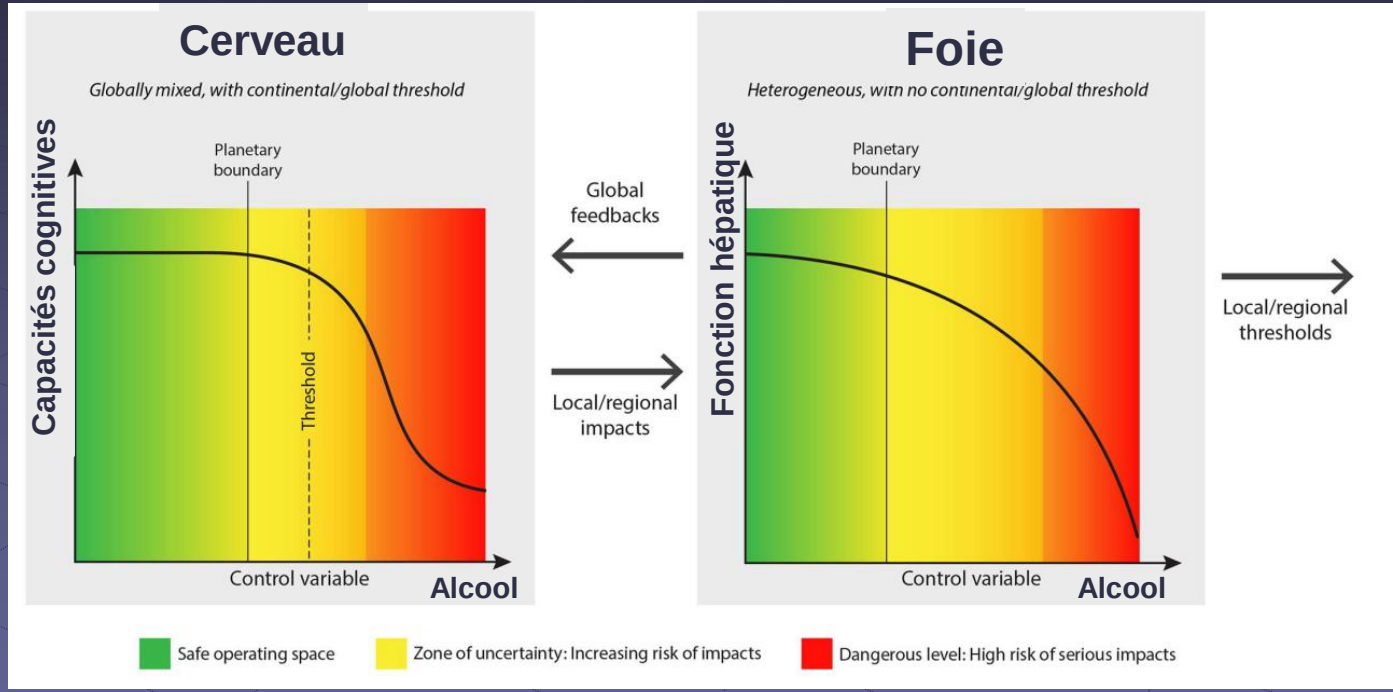
- ou avoir un impact important sur un autre organe
- l'Holocène définit l'état de bonne santé de référence.



Variable à seuil

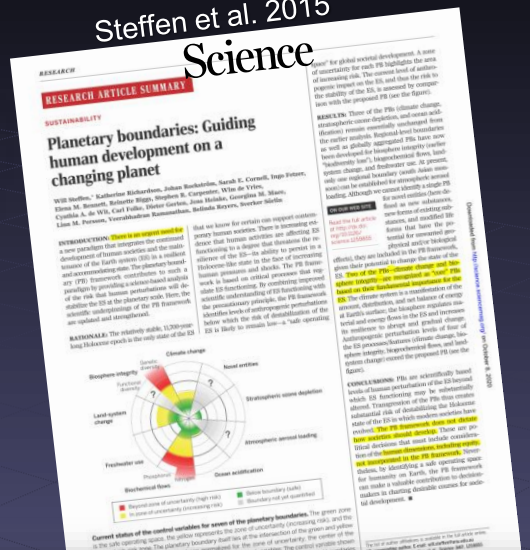
Seuil non défini

Limites Planétaires: où en est-on?

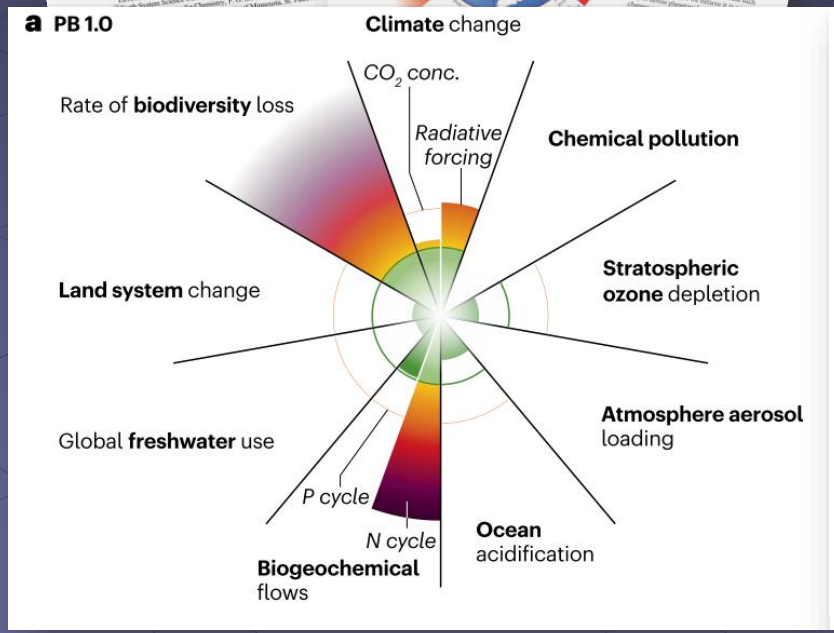
Rockström et al. 2009a

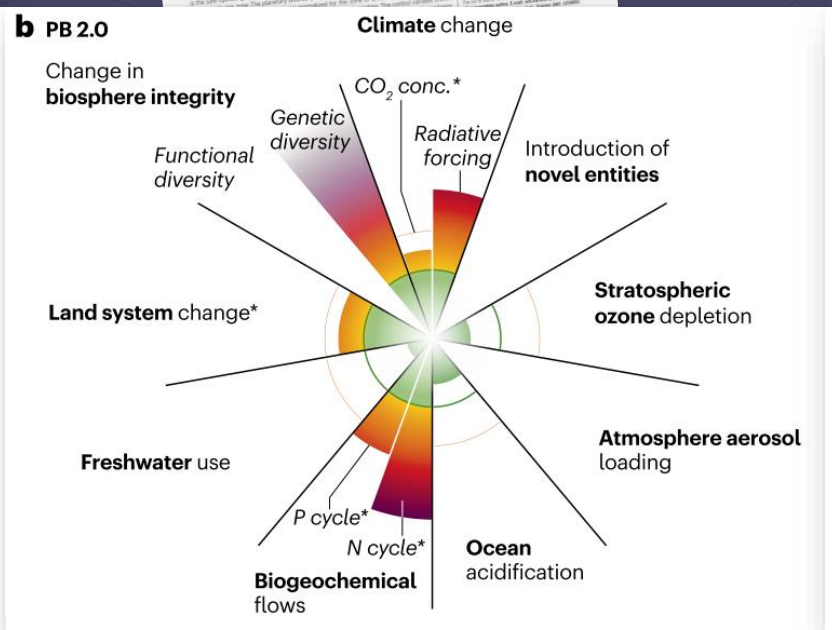
Rockström et al. 2009b

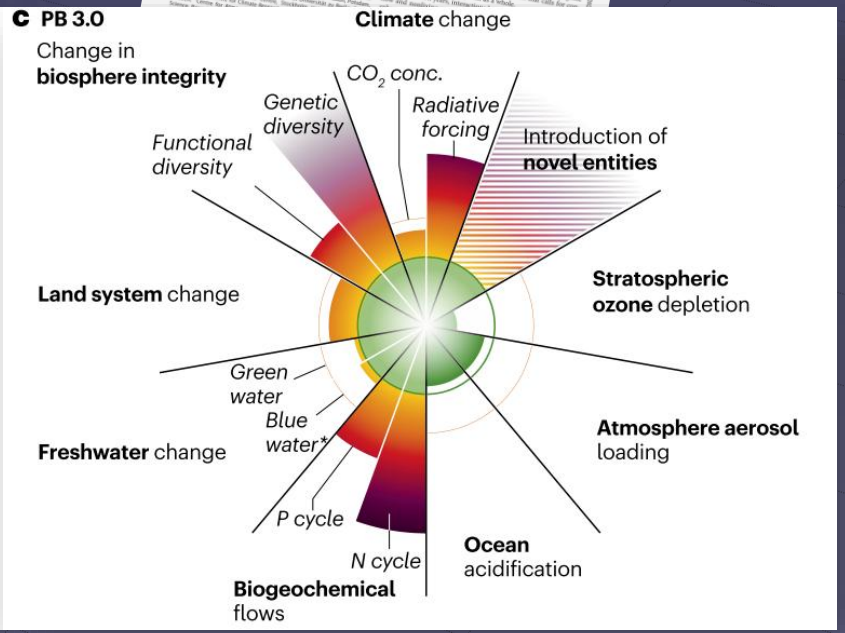
Steffen et al. 2015



Richardson et al. 2023







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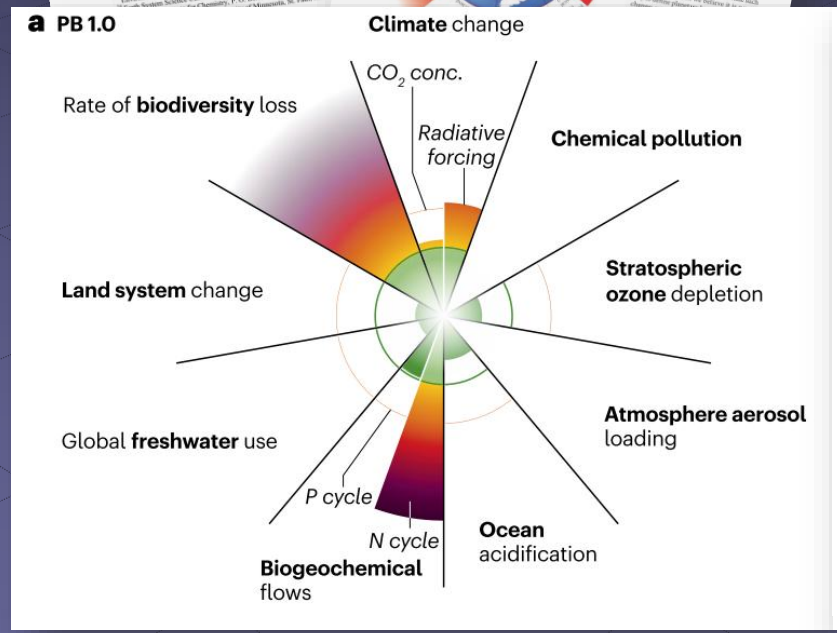
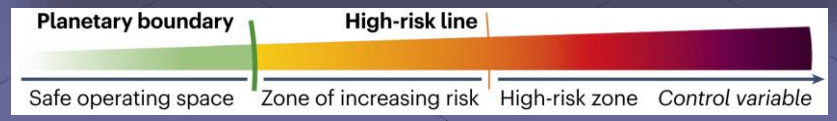
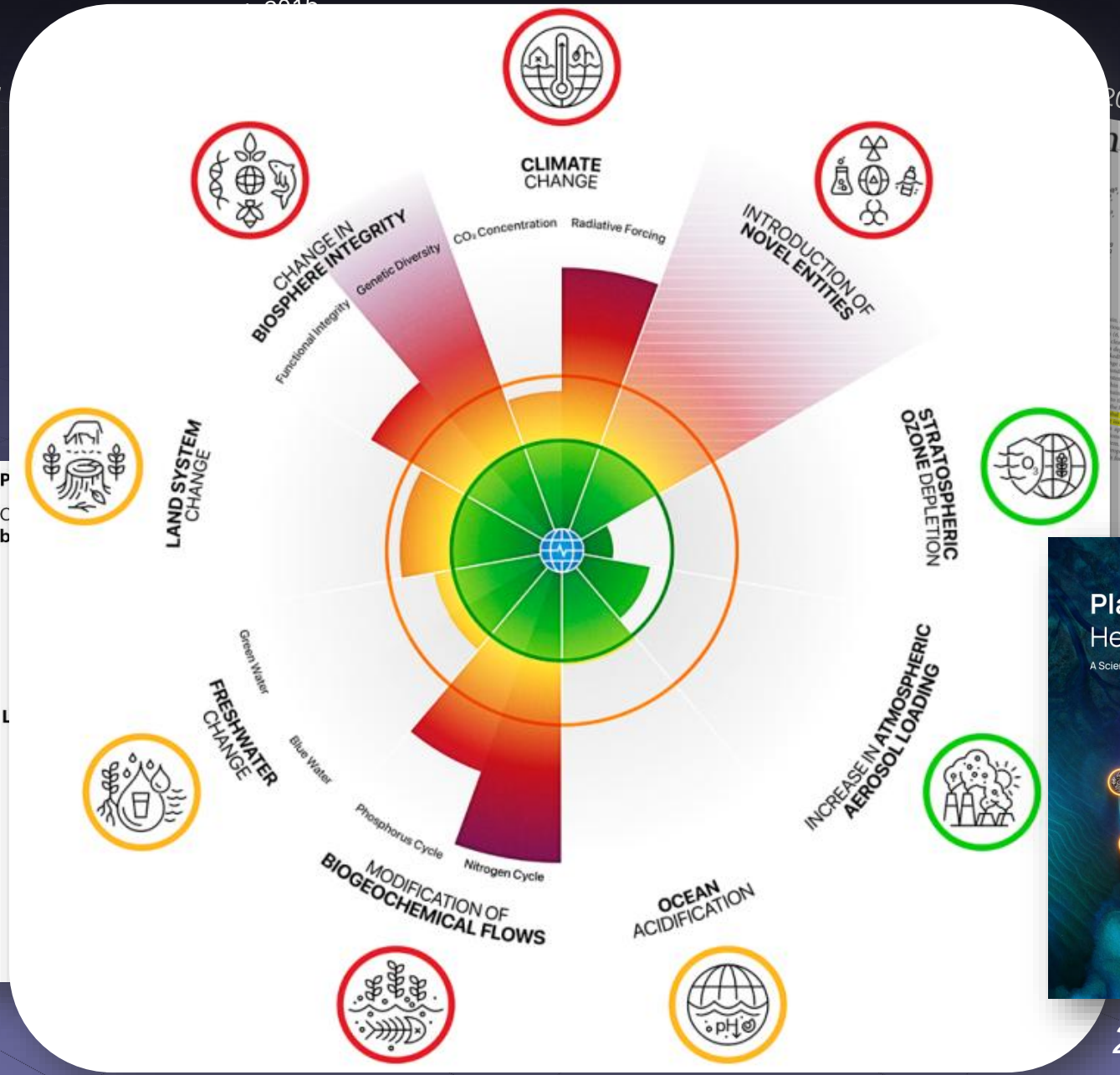
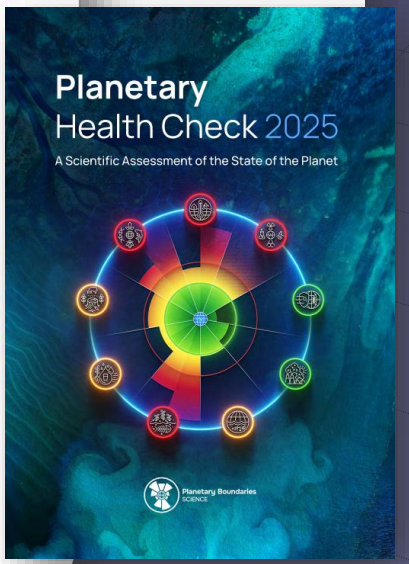
2023









24/09/2025

Quelle science derrière le concept ?

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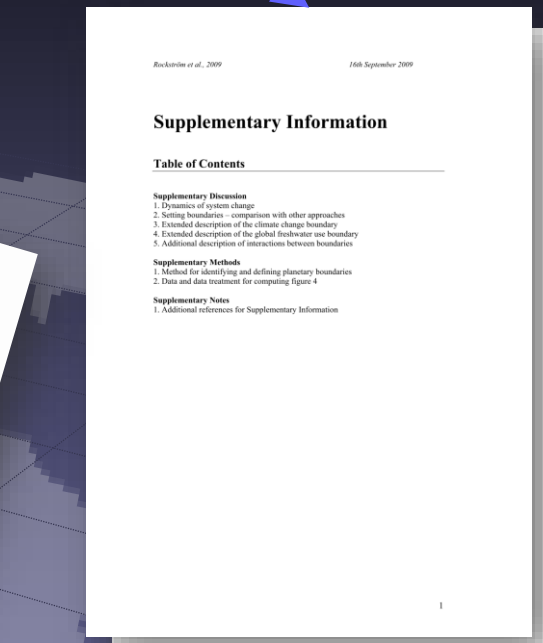
!! Non peer-reviewed !!

Approndissement

Rockström et al. 2009a,
Ecology & Society

Approfondissement

Fondements scientifiques



Quelle science derrière le concept ?

Dynamique des systèmes

Supplementary Information

Table of Contents

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
2. Data and data treatment for computing figure 4

Supplementary Notes
1. Additional references for Supplementary Information

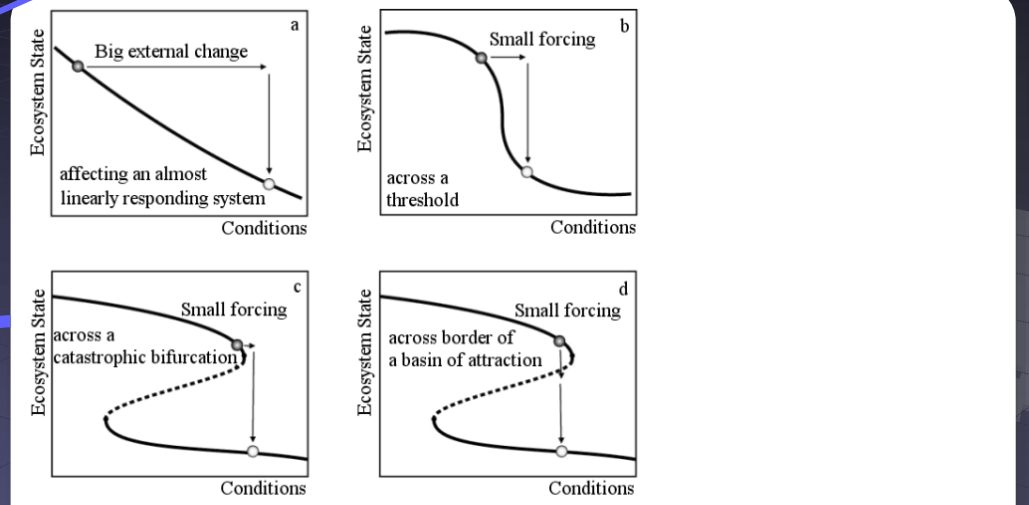
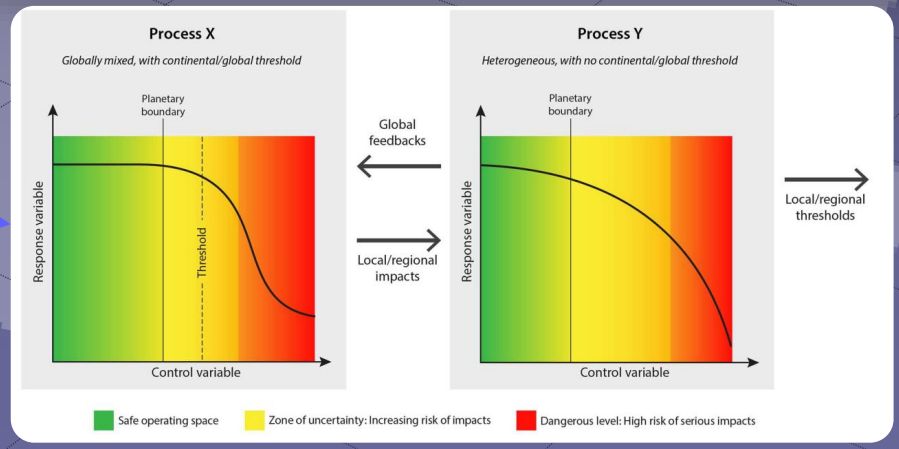


Figure S2. Degree of change in conditions required to generate large impacts in system state. For systems characterized by non-linear threshold dynamics a small forcing can generate large change, while systems responding largely linearly to change, will require big external change to cause large impacts.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



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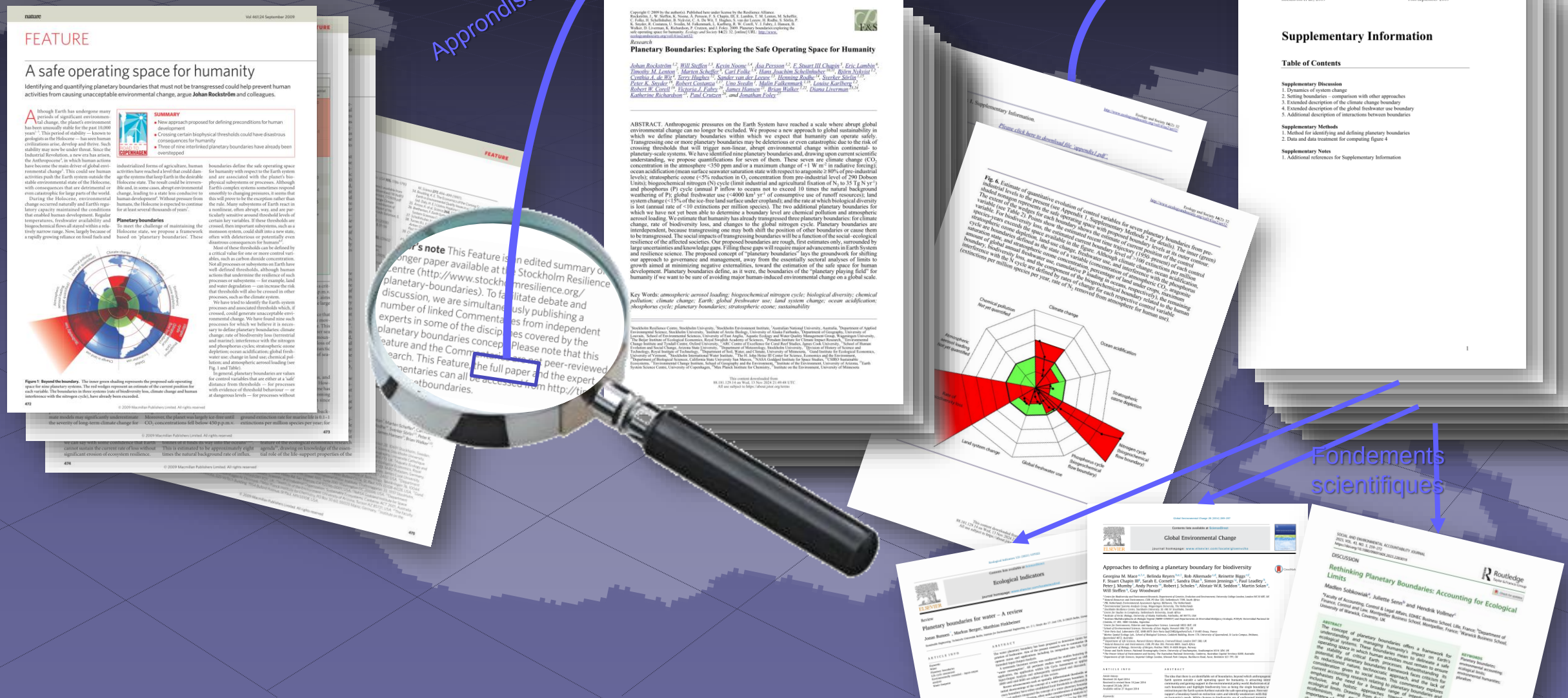

Quelle science derrière le concept ?

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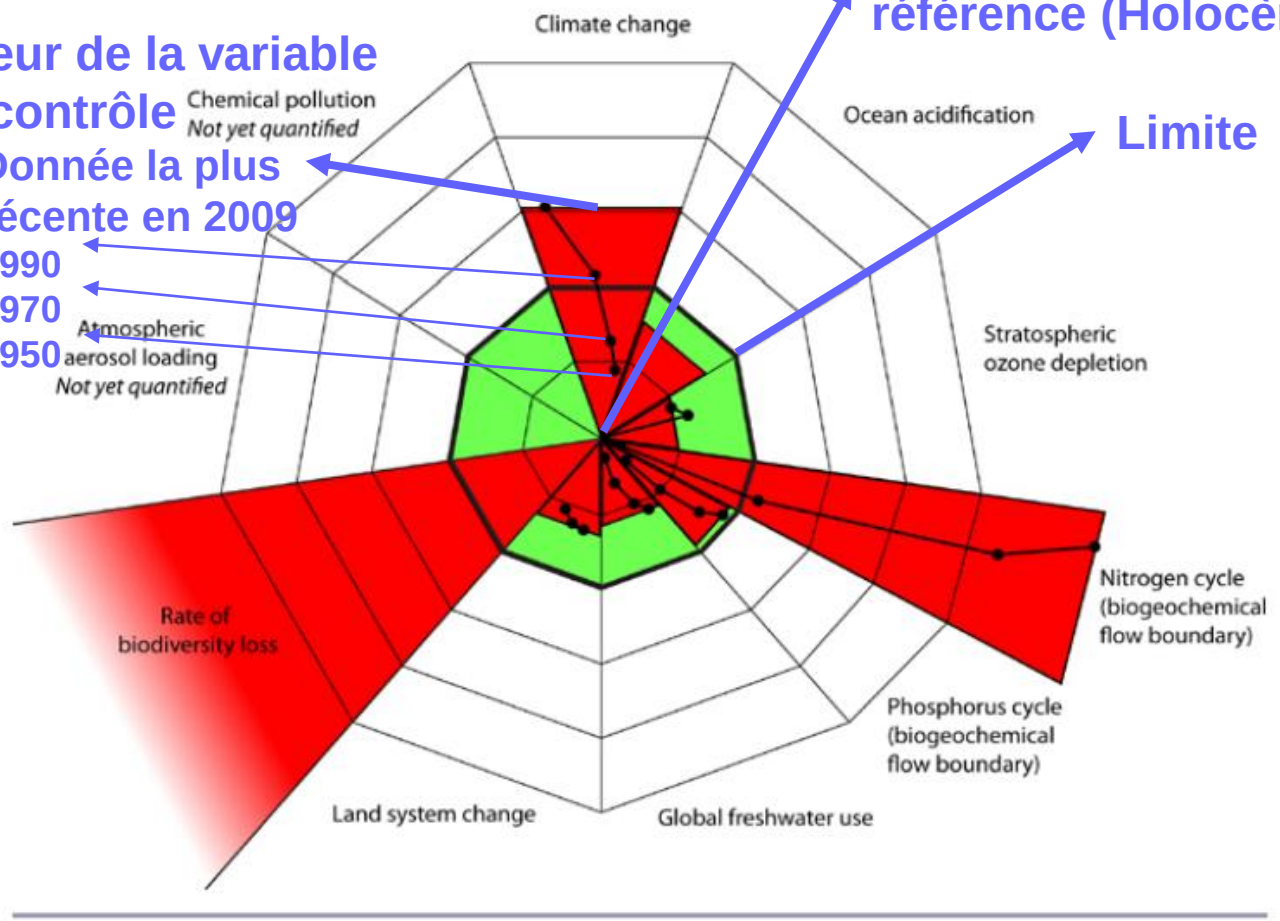
Valeur de la variable de contrôle

- Donnée la plus récente en 2009
- 1990
- 1970
- 1950

Niveau moyen de référence (Holocène)

Limite



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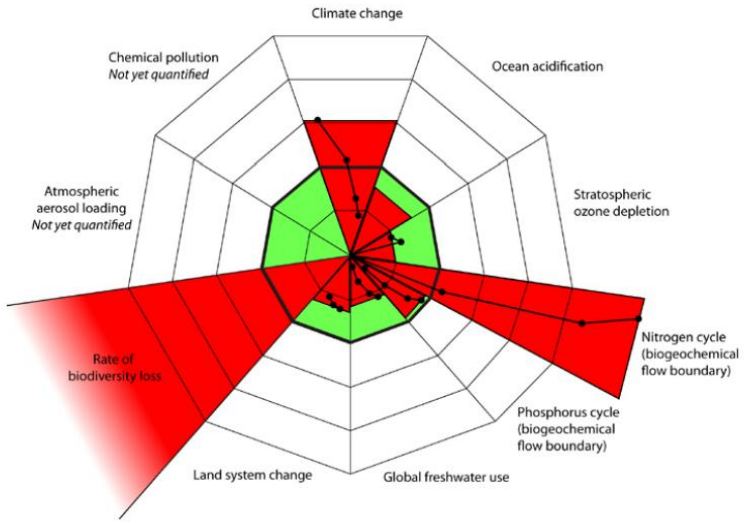
Quelle science derrière le concept ?

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 CO_2, 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 N_2 removed from atmosphere for human use).



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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 fresh-water 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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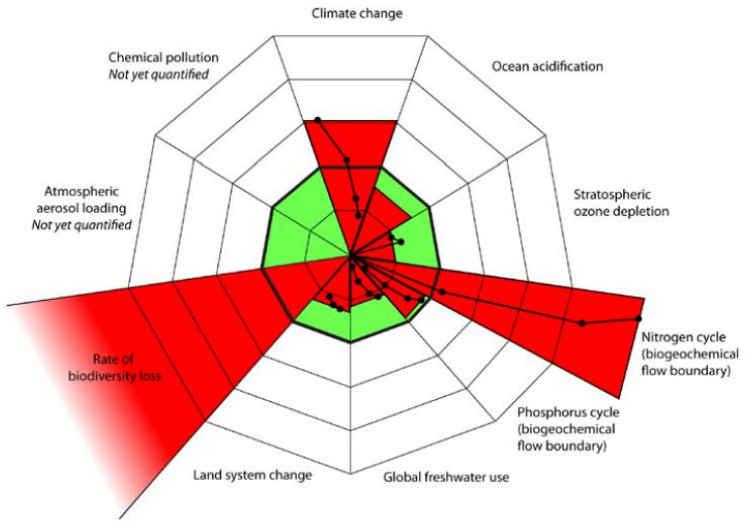

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Variable de contrôle

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 ?

Ecology and Society 14(2): 32
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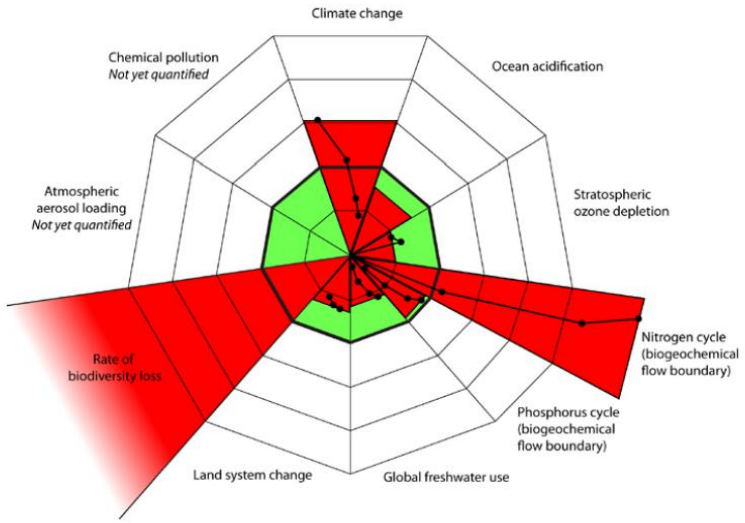

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Chemical pollution ***Not yet quantified***	-	-	-	-	-	-	-

Valeurs

Quantification basée sur

- Littérature scientifique
- Analyses spécifiques conduites au sein du consortium

Quelle science derrière le concept ?

Ecology and Society 14(2): 32
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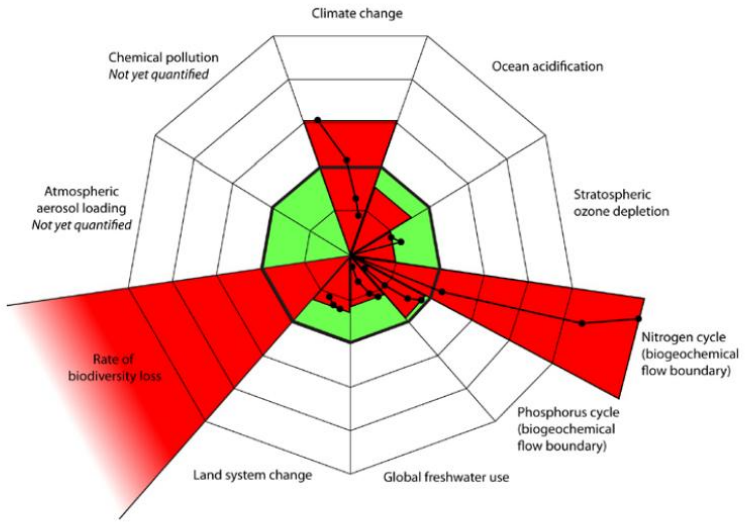

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Chemical pollution ***Not yet quantified***	-	-	-	-	-	-	-

Limites

Quantification arbitraires

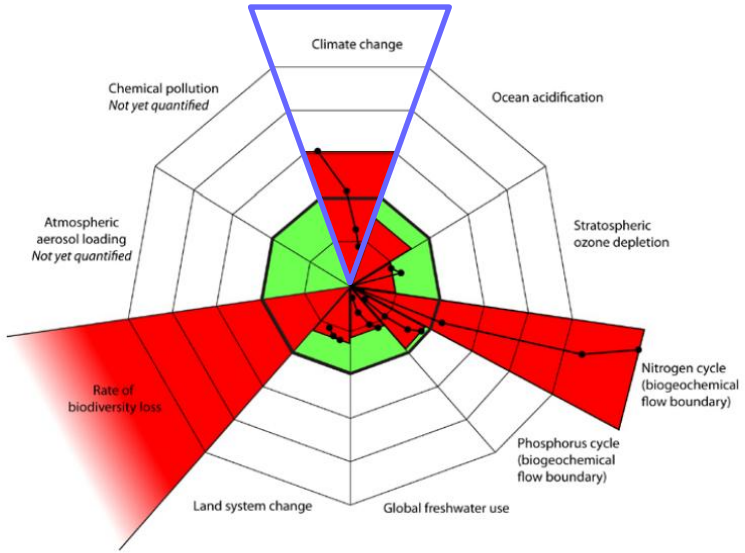
Subjectivité basée sur:

- 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 ?

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 CO_2, 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 N_2 removed from atmosphere for human use).



Rockström et al. 2009, Ecology & Society

Climate Change

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 paléo-climatiques (Hansen et al. 2008)

- **Variables de réponse**
  - Calottes polaires
  - Température du globe
- **Effet sur la température globale**
  - → **Rétroaction rapides**
  - Modèle de climat IPCC (2007): $[CO_2]x2$ → ΔT ~ + 3°C
  - → **Rétroactions lentes**
  - Entre -20000 ans et -10000 ans: $[CO_2]x2$ → 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 ?

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

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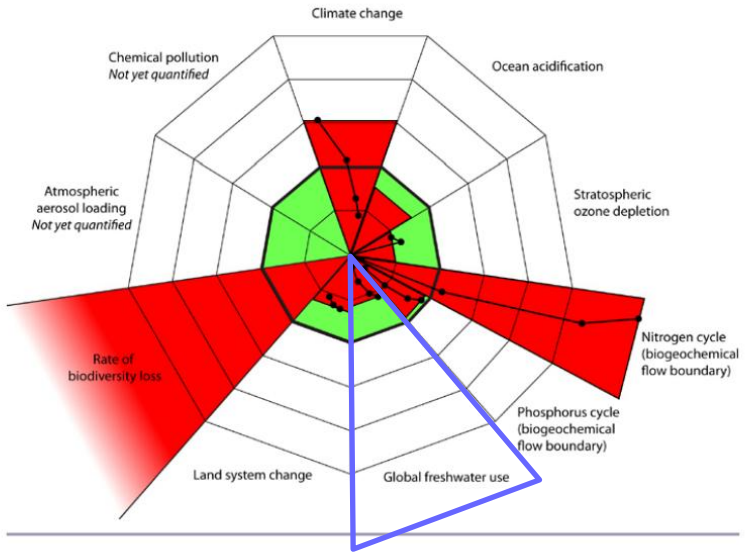
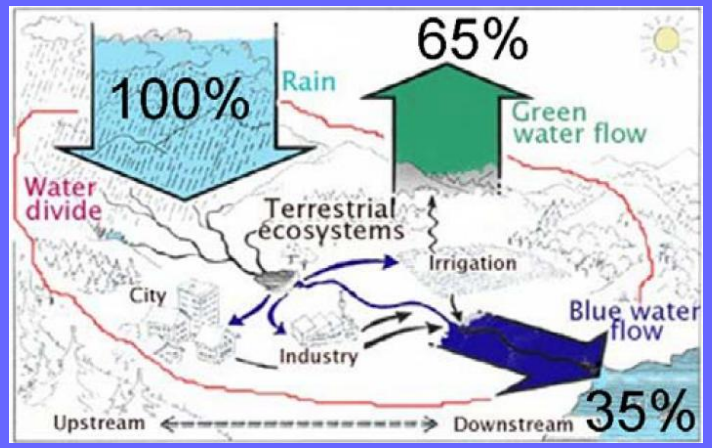


Rockström et al. 2009, Ecology & Society

Global freshwater use

Variable de contrôle	Seuil critique	Limite (safe)	Valeur (2009)
Prélèvement Eau Bleue	4000 – 6000 km³/an	4000 km³/an	2600 km³/an



- **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)

- 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

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 /an

  → **Assèchement de 25% rivières**

  → **30-35% population risque de manquer d'eau**

Quelle science derrière le concept ?

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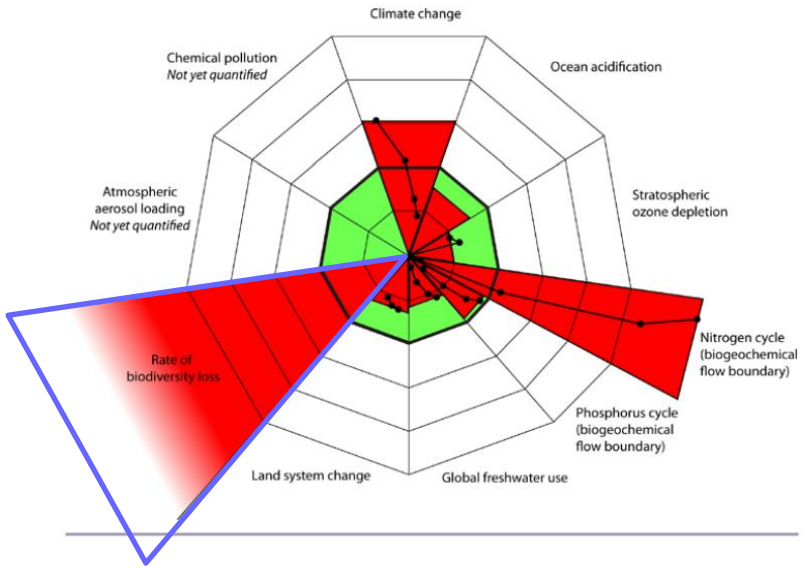


Rockström et al. 2009, Ecology & Society

Rate of biodiversity loss

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**

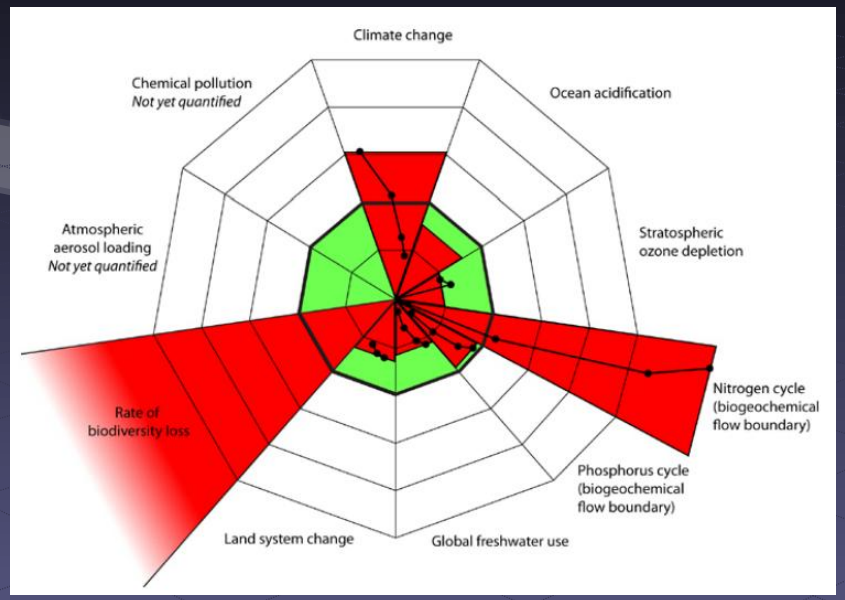
- Existent à l'échelle locale
- Manque de connaissances pour être défini à l'échelle globale

- **Choix de la limite**

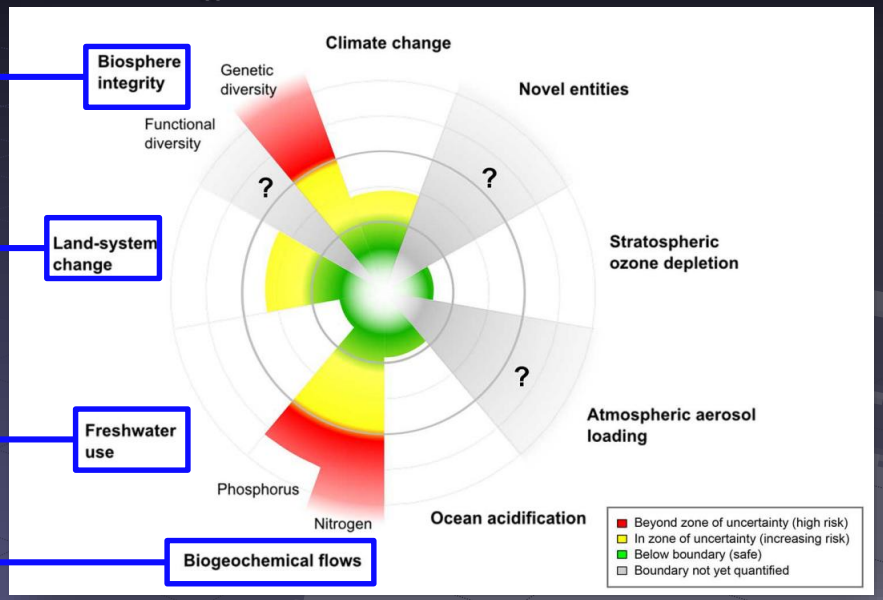
- 10 E/Msy estimation incertaine d'un seuil moyen global Holocène
- Dépassé quoi qu'il en soit

Evolution des limites planétaires

Rockström et al. 2009, Ecology & Society



Steffen et al. 2015, Science



Proposition de seuils régionaux

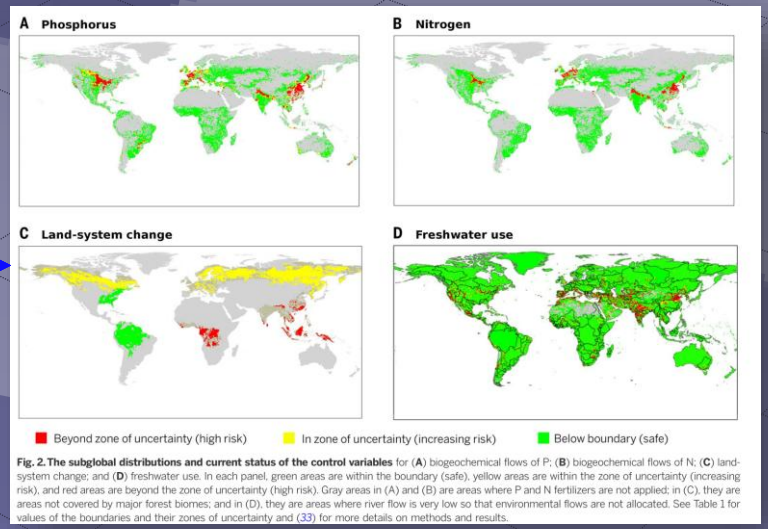


Fig. 2. The subglobal distributions and current status of the control variables for (**A**) biogeochemical flows of P; (**B**) biogeochemical flows of N; (**C**) land-system change; and (**D**) freshwater use. In each panel, green areas are within the boundary (safe), yellow areas are within the zone of uncertainty (increasing risk), and red areas are beyond the zone of uncertainty (high risk). Gray areas in (A) and (B) are areas where P and N fertilizers are not applied; in (C), they are areas not covered by major forest biomes; and in (D), they are areas where river flow is very low so that environmental flows are not allocated. See Table 1 for values of the boundaries and their zones of uncertainty and (*33*) for more details on methods and results.

Inchangé (sauf valeur récente)
- Climate Change
- Stratospheric Ozone depletion
- Ocean acidification

Chgt noms de processus
- Biosphere integrity
- Biogeochmical flows

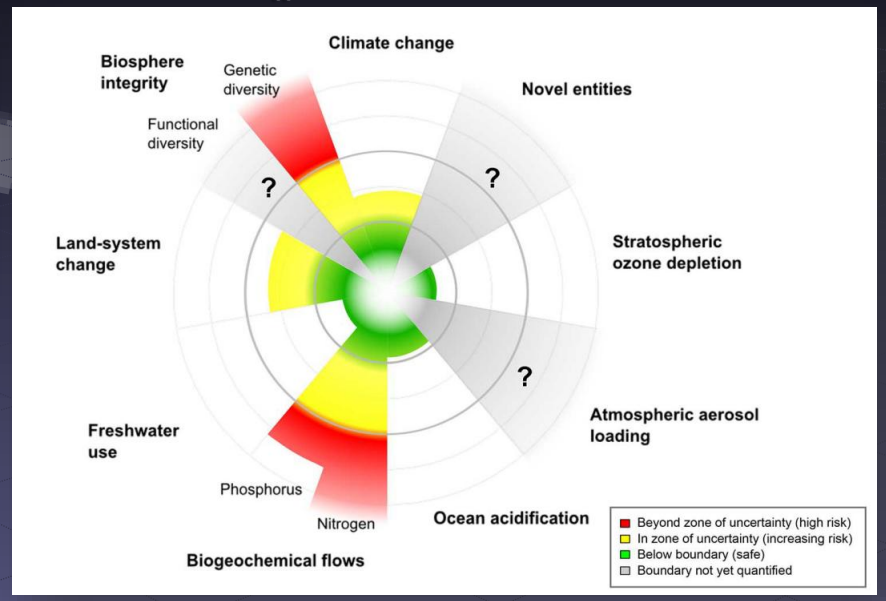
Chgt variables de contrôle
- Genetic diversity
- Function diversity

Chgt estimation des seuils
- Phosphore/Nitrogen
- Land system change

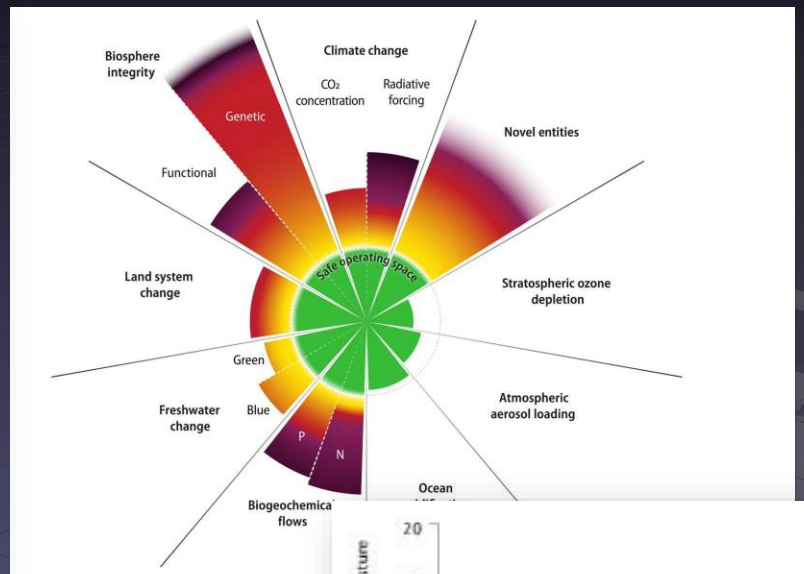
Mise en garde
- Hiérarchisation
- Pas prévu pour usage à échelle nationale ou locale
- « Planetary Boundary thinking » reste à élaborer à ces échelles

Evolution des limites planétaires

Steffen et al. 2015, Science



Richardson et al. 2023, Science Advances



Tous les processus et variables sont documentés

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.

Changement d

- La notion de
  remplacée u
  d'augmentat
  Par exple
  correspon
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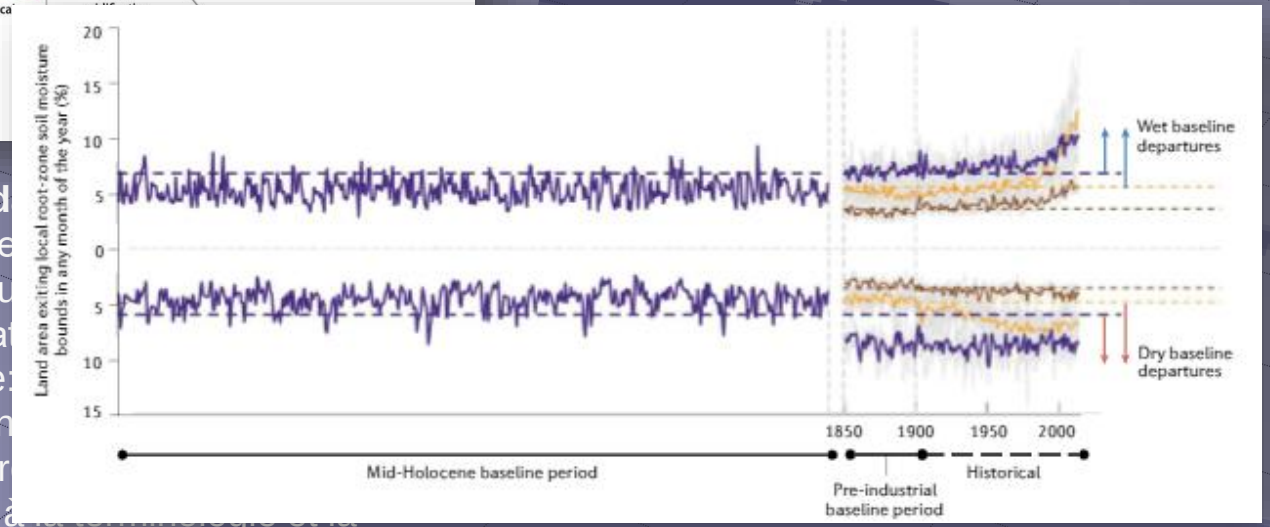
  → Coller à
  sémiologie du GIEC
- Mais le passage à haut risque reste extrêmement difficile à définir….



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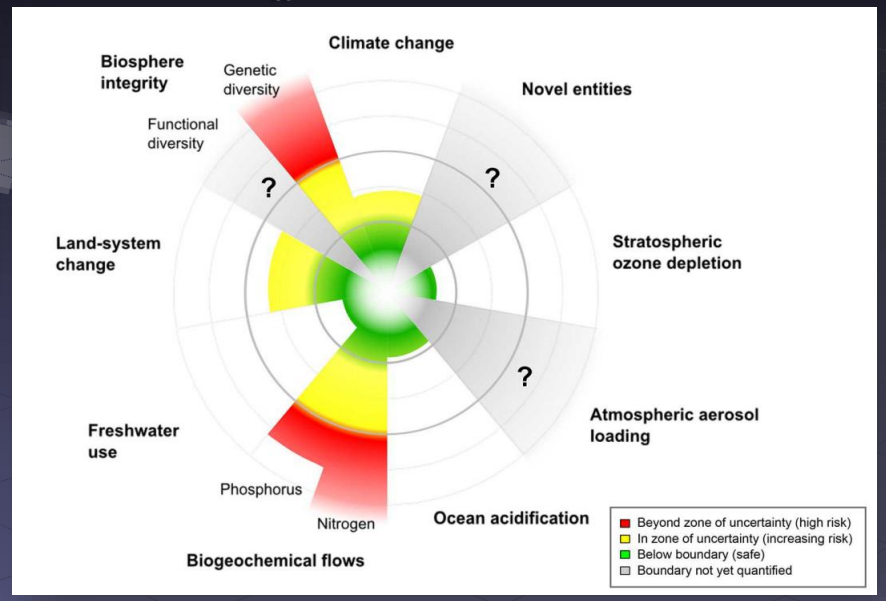

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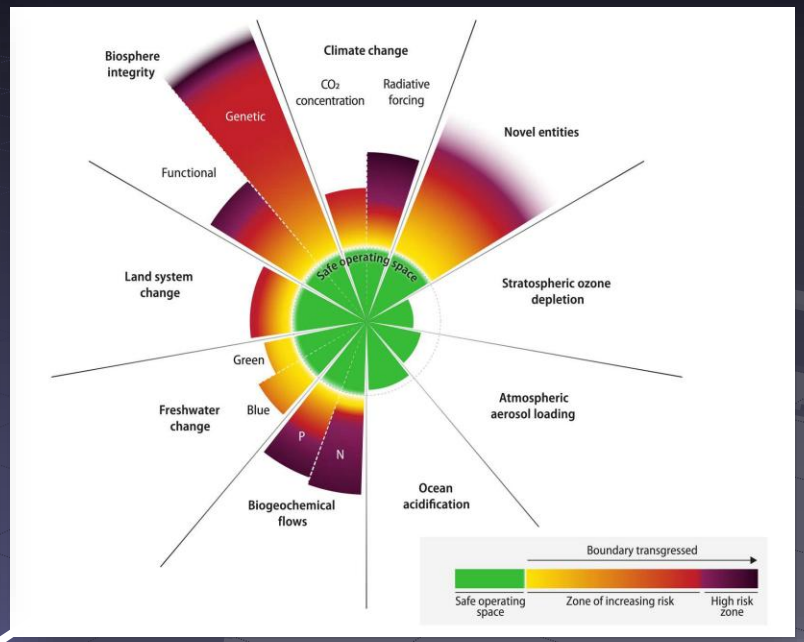


Tous les processus et variables sont documentés

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 sémiologie du GIEC
- Mais le passage à haut risque reste extrêmement difficile à définir….

Fresh water défini de façon plus lisible.

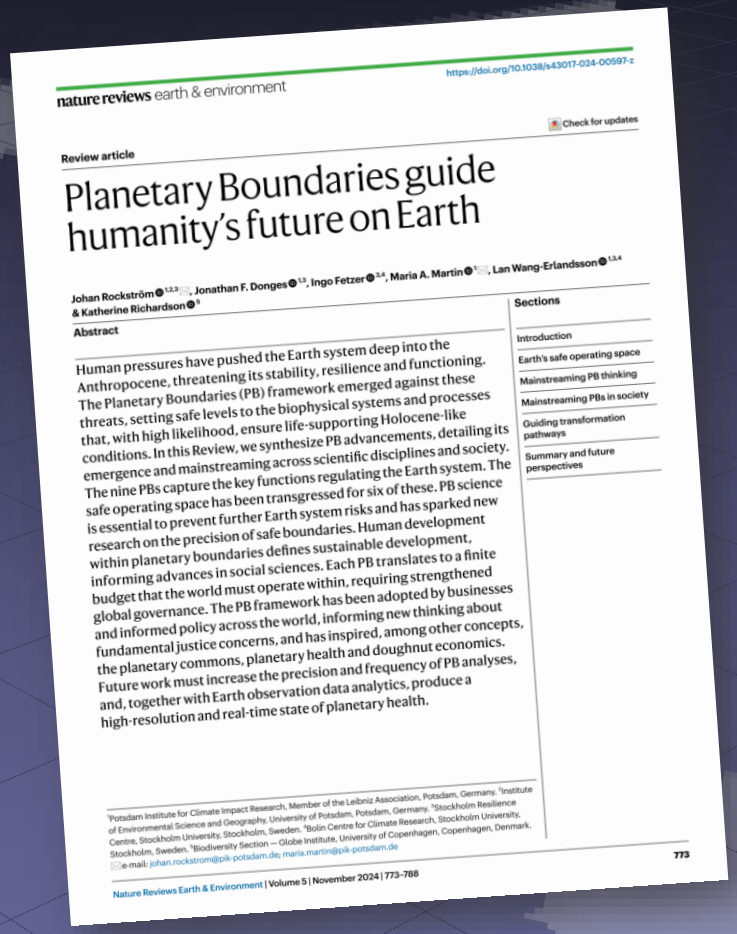
- **Variables de contrôle**
  - proxys séparés de blue et green water
  - Évaluation de la déviation temporelle de la variabilité par rapport à l'Holocène
- **Seuil**
  - Le seuil est défini au 95th percentile de la variabilité naturelle et la variabilité sort de cette zone pour près de 20% de la zone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

Functional Biodiversity

- **Variable de Contrôle**
  - Human Appropriation of Net Primary Production (appropriation anthropique 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

Evolution des limites planétaires

Rockström et al. 2024, Nature Reviews



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Review article

Planetary Boundaries guide humanity's future on Earth

Johan Rockström[1,2,3] ✉, Jonathan F. Donges[1,3], Ingo Fetzer[3,4], Maria A. Martin[1] ✉, Lan Wang-Erlandsson[1,3,4] & Katherine Richardson[5]

Abstract

Human pressures have pushed the Earth system deep into the Anthropocene, threatening its stability, resilience and functioning. The Planetary Boundaries (PB) framework emerged against these threats, setting safe levels to the biophysical systems and processes that, with high likelihood, ensure life-supporting Holocene-like conditions. In this Review, we synthesize PB advancements, detailing its emergence and mainstreaming across scientific disciplines and society. The nine PBs capture the key functions regulating the Earth system. The safe operating space has been transgressed for six of these. PB science is essential to prevent further Earth system risks and has sparked new research on the precision of safe boundaries. Human development within planetary boundaries defines sustainable development, informing advances in social sciences. Each PB translates to a finite budget that the world must operate within, requiring strengthened global governance. The PB framework has been adopted by businesses and informed policy across the world, informing new thinking about fundamental justice concerns, and has inspired, among other concepts, the planetary commons, planetary health and doughnut economics. Future work must increase the precision and frequency of PB analyses, and, together with Earth observation data analytics, produce a high-resolution and real-time state of planetary health.

Sections

Introduction
Earth's safe operating space
Mainstreaming PB thinking
Mainstreaming PBs in society
Guiding transformation pathways
Summary and future perspectives

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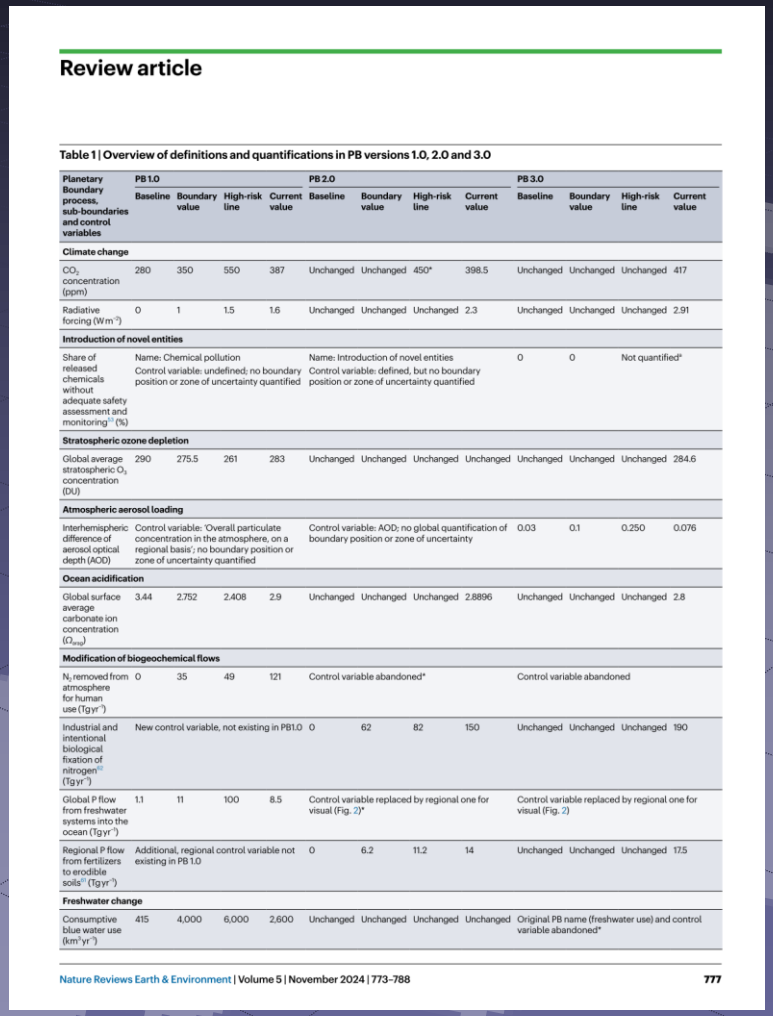
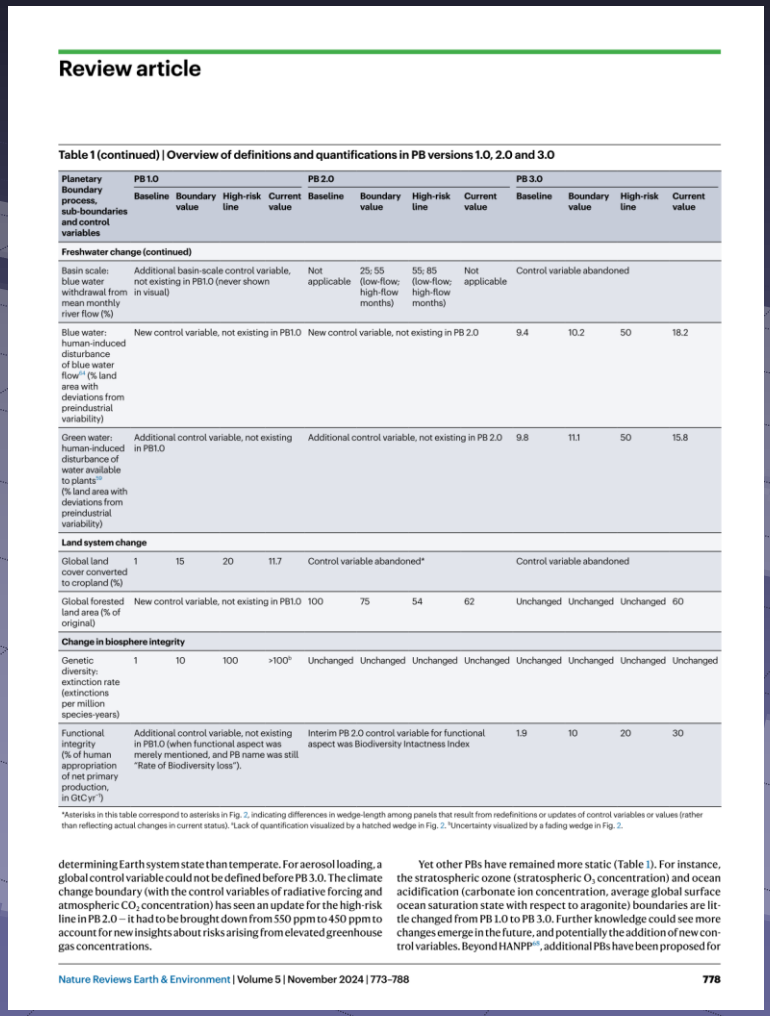


Table 1 | Overview of definitions and quantifications in PB versions 1.0, 2.0 and 3.0

Planetary Boundary process, sub-boundaries and control variables	PB 1.0				PB 2.0				PB 3.0			
	Baseline	Boundary value	High-risk line	Current value	Baseline	Boundary value	High-risk line	Current value	Baseline	Boundary value	High-risk line	Current value
Climate change												
CO_2 concentration (ppm)	280	350	550	387	Unchanged	Unchanged	450*	398.5	Unchanged	Unchanged	Unchanged	417
Radiative forcing ($W m^{-2}$)	0	1	1.5	1.6	Unchanged	Unchanged	Unchanged	2.3	Unchanged	Unchanged	Unchanged	2.91
Introduction of novel entities												
Share of released chemicals without adequate safety assessment and monitoring[52] (%)	Name: Chemical pollution Control variable: undefined; no boundary position or zone of uncertainty quantified				Name: Introduction of novel entities Control variable: defined, but no boundary position or zone of uncertainty quantified				0	0	Not quantified*	
Stratospheric ozone depletion												
Global average stratospheric O_3 concentration (DU)	290	275.5	261	283	Unchanged	Unchanged	Unchanged	Unchanged	Unchanged	Unchanged	Unchanged	284.6
Atmospheric aerosol loading												
Interhemispheric difference of aerosol optical depth (AOD)	Control variable: 'Overall particulate concentration in the atmosphere, on a regional basis'; no boundary position or zone of uncertainty quantified				Control variable: AOD; no global quantification of boundary position or zone of uncertainty				0.03	0.1	0.250	0.076
Ocean acidification												
Global surface average carbonate ion concentration (Ω_{arag})	3.44	2.752	2.408	2.9	Unchanged	Unchanged	Unchanged	2.8896	Unchanged	Unchanged	Unchanged	2.8
Modification of biogeochemical flows												
N_2 removed from atmosphere for human use ($Tg yr^{-1}$)	0	35	49	121	Control variable abandoned*				Control variable abandoned			
Industrial and intentional biological fixation of nitrogen[92] ($Tg yr^{-1}$)	New control variable, not existing in PB1.0				0	62	82	150	Unchanged	Unchanged	Unchanged	190
Global P flow from freshwater systems into the ocean ($Tg yr^{-1}$)	1.1	11	100	8.5	Control variable replaced by regional one for visual (Fig. 2)*				Control variable replaced by regional one for visual (Fig. 2)			
Regional P flow from fertilizers to erodible soils[93] ($Tg yr^{-1}$)	Additional, regional control variable not existing in PB 1.0				0	6.2	11.2	14	Unchanged	Unchanged	Unchanged	17.5
Freshwater change												
Consumptive blue water use ($km^3 yr^{-1}$)	415	4,000	6,000	2,600	Unchanged	Unchanged	Unchanged	Unchanged	Original PB name (freshwater use) and control variable abandoned*			



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	Baseline	Boundary value	High-risk line	Current value	Baseline	Boundary value	High-risk line	Current value	Baseline	Boundary value	High-risk line	Current value
Freshwater change (continued)												
Basin scale: blue water withdrawal from mean monthly river flow (%)	Additional basin-scale control variable, not existing in PB1.0 (never shown in visual)				Not applicable	25; 55 (low-flow; high-flow months)	55; 85 (low-flow; high-flow months)	Not applicable	Control variable abandoned			
Blue water: human-induced disturbance of blue water flow[49] (% land area with deviations from preindustrial variability)	New control variable, not existing in PB1.0				New control variable, not existing in PB 2.0				9.4	10.2	50	18.2
Green water: human-induced disturbance of water available to plants[59] (% land area with deviations from preindustrial variability)	Additional control variable, not existing in PB1.0				Additional control variable, not existing in PB 2.0				9.8	11.1	50	15.8
Land system change												
Global land cover converted to cropland (%)	1	15	20	11.7	Control variable abandoned*				Control variable abandoned			
Global forested land area (% of original)	New control variable, not existing in PB1.0				100	75	54	62	Unchanged	Unchanged	Unchanged	60
Change in biosphere integrity												
Genetic diversity: extinction rate (extinctions per million species-years)	1	10	100	>100[b]	Unchanged	Unchanged	Unchanged	Unchanged	Unchanged	Unchanged	Unchanged	Unchanged
Functional integrity (% of human appropriation of net primary production, in $GtC yr^{-1}$)	Additional control variable, not existing in PB1.0 (when functional aspect was merely mentioned, and PB name was still "Rate of Biodiversity loss").				Interim PB 2.0 control variable for functional aspect was Biodiversity Intactness Index				1.9	10	20	30

*Asterisks in this table correspond to asterisks in Fig. 2, indicating differences in wedge-length among panels that result from redefinitions or updates of control variables or values (rather than reflecting actual changes in current status). [b]Lack of quantification visualized by a hatched wedge in Fig. 2. [a]Uncertainty visualized by a fading wedge in Fig. 2.

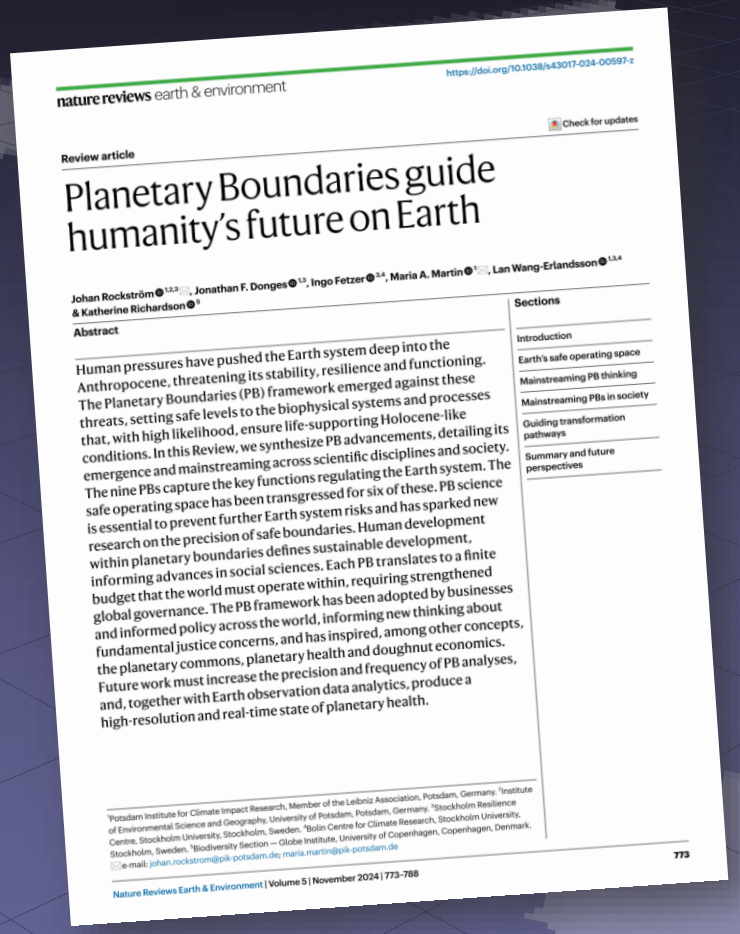
determining Earth system state than temperate. For aerosol loading, a global control variable could not be defined before PB 3.0. The climate change boundary (with the control variables of radiative forcing and atmospheric CO_2 concentration) has seen an update for the high-risk line in PB 2.0 – it had to be brought down from 550 ppm to 450 ppm to account for new insights about risks arising from elevated greenhouse gas concentrations.

Yet other PBs have remained more static (Table 1). For instance, the stratospheric ozone (stratospheric O_3 concentration) and ocean acidification (carbonate ion concentration, average global surface ocean saturation state with respect to aragonite) boundaries are little changed from PB 1.0 to PB 3.0. Further knowledge could see more changes emerge in the future, and potentially the addition of new control variables. Beyond HANPP[98], additional PBs have been proposed for

Pour une synthèse plus lisible

Evolution des limites planétaires

Rockström et al. 2024, Nature Reviews



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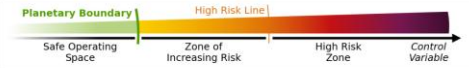
Pour une synthèse plus lisible

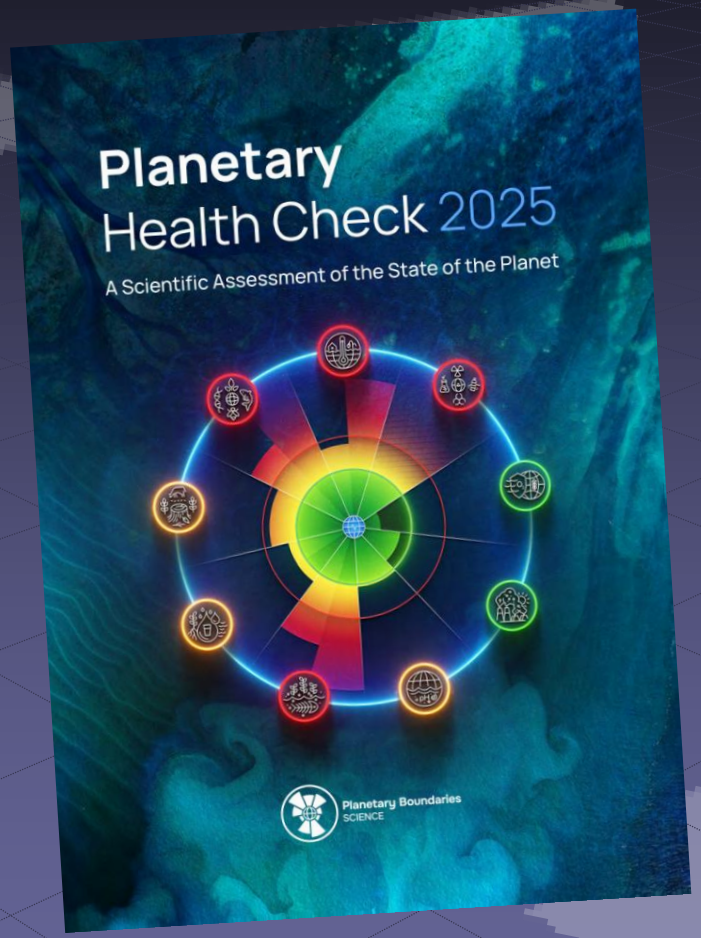
Supplementary Table 1 – Glossary

Glossary:	
Planetary Boundaries (PB) Framework	A theoretical and methodological framework emerging from Earth system science quantifying safe boundary levels for human perturbation of critical Earth system processes. The framework identifies the biophysical processes and systems that together regulate the functioning of life-support systems, and the resilience and stability of the planet. In other words, it is ultimately a measure of the state of the planet Nine "**Planetary Boundaries"** have been identified. For each of the Earth system processes/systems, one or more **control variables** are identified. A quantitative assessment is made for each of these control variables, quantifying the boundary level within which there is a high chance of maintaining Earth system functions and the state of the planet within Holocene-like inter-glacial conditions. Together, these quantifications provide a **safe operating space** for human development on Earth. Taken together, the framework defines **Planetary Boundaries** that characterise Earth's biophysical departure from Holocene conditions and alerts to the rising risks in the Anthropocene.
Planetary Boundary *Denoting:* a) The outer bounds of the safe operating space; *but also refers to:* b) the nine **planetary-boundary processes**.	This term is denoting: a) The outer bounds of the Holocene-like safe operating space (for example "The Climate Change boundary is transgressed"), but also widely used to refer to: b) the individual human-changed Earth-system processes in the Planetary Boundaries Framework, the planetary-boundary processes (for example "the Climate Change boundary is outside of the safe space". A more precise formulation would be "the planetary boundary process *Climate Change* is outside of the safe operating space")
Planetary Boundary process	Strictly speaking, the PB framework includes Earth System "processes" (such as carbon cycling translating into climate forcing) and "systems" (such as critical biomes like the temperate and tropical forests). In short, this is often denoted as "the **nine PB processes",** but sometimes they are defined as "domains", and other times more precisely as "processes and systems". The nine Planetary Boundary processes (and systems) include the following: Climate Change; Introduction of Novel Entities; Stratospheric Ozone Depletion; Atmospheric Aerosol Loading; Ocean Acidification; Modification of Biogeochemical Flows; Freshwater Change; Land System Change; Change in Biosphere Integrity. *Three of these are split for the sake of refinement: Modification of Biogeochemical Flows; Freshwater Change and Change in Biosphere Integrity. Climate change is currently represented by two control variables.* This set comprehensively covers aspects of Earth System functioning that have conferred comparative stability at planetary scale over timescales of centuries to thousands of years.
Illustration to support the following rows:	
Safe operating space	Keeping all Earth system regulating processes within safe boundaries that provide a high chance of safeguarding Holocene-like conditions on Earth. Together, the planetary boundaries for the Earth system processes included in the framework delineate a safe operating space for humanity, i.e., where there is little risk that anthropogenic activities will lead to dramatic and potentially irreversible changes in the state of the Earth system (overall global environmental conditions).
Risk and damage	Risk is defined as damage multiplied with probability (of the damage). The damage referred to in the PB context is structured as follows: 1. Potential top-level damage, for the case where all nine boundaries are transgressed: a. Losing a Holocene-like ES state / destabilizing Holocene-like ES state / change in functioning of the ES b. Substantially eroding ES resilience 2. Lower-level damage, for the case individual boundaries are transgressed: a. Destabilization of the respective processes, undermining functions at regional to global scales (with potential risks of feedbacks and interactions) b. Regime shifts / crossing thresholds (with high risk of reinforcing feedbacks)
Risk levels/risk zones	Risk levels are derived from the different levels of probability for the specific **damage** in PB context, as described above. Only two of three zones can be described with (high) confidence: *Green:* The **safe operating space**, where the low **risk** describes a low probability of **damage**. *Orange/Red/Purple:* The high **risk** zone where there is a much higher probability of **damage**. The intermediate zone (referred to as **zone of uncertainty** in PB1.0 and PB2.0 and **/zone of increasing risk** in PB3.0) is a special case *(Yellow/Orange)*(see below in glossary).
Zone of increasing risk (formerly referred to as zone of uncertainty) And placement of upper and lower ends	For each Planetary boundary, **control variable(s)** are selected, and the state of scientific knowledge on risk (related to loss of function and deviating from Holocene-like conditions) assessed. The resulting uncertainty range in science defines the zone increasing risk. The **Planetary Boundary** is placed just below the point where scientific evidence shows that risks of perturbing the overall function and state of the Earth system, increases with further transgression of the boundary. This is a normative choice in the PB framework, justified by applying the precautionary principle, given that the impact of long-term PB transgression can be extremely high, making risk very high, even if probability is low (risk = impact x probability). The high risk line is placed at the upper end of the zone of increasing risk, but its quantification and the underlying reasoning for its placement is associated with a notably higher degree of uncertainty compared to the planetary boundary. *Increasing Risk:* All that can be said with high confidence for this zone is that the **risk** (=the probability of **damage** in PB context) is increasing from the lower to the upper end. However, the zone was renamed in

	PB3.0 from "zone of uncertainty" to "zone of increasing risk", because all evidence indicates that further away from the safe boundary level leads to higher risk. *Uncertainty:* Gaps and weaknesses in the scientific knowledge base do not allow for a more precise description with confidence. Additionally, intrinsic uncertainties in the functioning of the ES might make it fundamentally impossible to assign a specific risk level (be it low, intermediate, or high probability of **damage**) within this zone.
Control variable	Measurable variables closely associated with the state of the nine **PB processes**, with data allowing the quantification of an appropriate **boundary value at the planetary scale**. Pragmatic approaches are sometimes required, due to data availability, where proxy-variables are used as "2nd best" representatives of the state of a planetary boundary (for example, extinction rate was originally adopted as a proxy indictor for both genetic and functional diversity, and was later complemented by better control variables for functional diversity (BII and HANPP). *In the case of Climate Change, Change in Biosphere Integrity, Freshwater Change, and Modification of Biogeochemical Flows, there are two control variables for the same ES process, capturing different dimensions of each boundary (CO2/total radiative forcing; genetic/functional diversity; green/blue; N/P)*
Boundary value (of the control variable)	Value of the **control variable** that determines the Planetary Boundary position.
Current value (of the control variable)	Value of the **control variable** that determines the magnitude of contemporary human-caused perturbation to the respective **planetary boundary process**.
Planetary Boundary science	Scientific work and output that, based on the established **PB framework**, is explicitly designed to: 1. Identify appropriate **control variables**; 2. Quantify the associated **boundary values** and **current values**; 3. Describe the **risks (damage and probabilities)** associated with transgression of the boundaries; 4. Describe and quantify the **uncertainties** involved; 5. Describe **interactions** for the set of nine **planetary-boundary processes**.
World-Earth system	The intertwined planetary system in the Anthropocene including biogeophysical Earth system processes (Earth), socio-economic and socio-cultural processes of human societies (World), and human-Earth system interactions and feedbacks. "World" refers here to complex human societies as embedded in the biophysical Earth system.
Planetary Boundary interactions (between the nine PB processes)	Planetary Boundary interactions refer to reciprocal influences among the nine boundaries. For example, climate change transgressions alter the freshwater cycle with subsequent consequences for the land carbon sink, which in turn can amplify the human pressure on climate change. Individual boundary positions in the PB framework are assessed assuming the absence of interactions with other PB processes. However, an overall planetary safe operating space ought to account for Earth system interactions, and might therefore not be identical to the aggregated space of the safe zones of each individual boundary.

Evolution des limites planétaires

Planetary Health Check, 2025



Pour une synthèse plus lisible

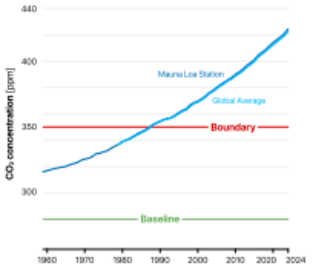
Control Variables

#1 Atmospheric CO_2 Concentration (CO_2)

Definition	Atmospheric CO_2 is a primary greenhouse gas emitted by human activities such as fossil fuel combustion, deforestation, and cement production. It is a key driver of Climate Change.[3] CO_2 is relatively straightforward to monitor through atmospheric measurements, satellite observations, and carbon budget assessments.
Unit	Parts per million (ppm)
Historical Range	Over the course of Earth's history, CO_2 levels have naturally fluctuated between about 180–200 ppm during ice ages and around 280 ppm during the pre-industrial Holocene period.[234]
Planetary Boundary (PB)	Scientists have proposed a PB for CO_2 at 350 ppm, based on paleoclimate evidence and climate modeling. This threshold represents a point beyond which the risks of triggering irreversible changes, such as large-scale melting of polar ice sheets, increase significantly.[92,235,236,237] It also aligns with the internationally recognized goal of limiting global warming to 1.5 °C above pre-industrial levels, as agreed upon in the Paris Climate Agreement.[4]

FIGURE 17 - Atmospheric CO_2 concentration far exceeds the safe level. This figure illustrates the steady increase in the atmospheric CO_2 concentration, as one of the **Climate Change** boundary's control variables. The dark blue line represents annual mean values from 1959 to 2024 at the Mauna Loa Observatory in Hawaii, operated by the National Oceanic and Atmospheric Administration (NOAA).[238] The light blue line shows globally averaged CO_2 concentrations from multiple international monitoring sites,[238] including Mauna Loa. The green and red lines indicate the baseline (safe) value (280 ppm) and the Planetary Boundary threshold (350 ppm) for this control variable, respectively.

Key takeaway: *CO_2 continues to rise and remains the dominant driver of climate change, with current levels approximately 50% above pre-industrial concentrations.*



#2 Total Anthropogenic Radiative Forcing at the Top of the Atmosphere (TOA)

Definition	The net radiative forcing sums up all the ways human activities impact the global climate. This includes emissions of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as well as aerosols and land-use changes. Radiative forcing is a key measure of how much additional heat energy is added to the Earth system. It integrates the effects of all human activities that influence the planet's energy balance and therefore represents the overall strength of human-induced climate change.[3] While direct TOA fluxes can be measured via satellites, estimating the human-caused component depends on climate models. This makes it a powerful, system-level signal, but also more abstract and less directly observable than CO_2 or temperature.
Unit	Watts per square meter (W/m^2)
Historical Range	During the pre-industrial Holocene, the radiative forcing remained relatively stable with small fluctuations due to land cover changes and volcanic activity,[239,240] indicating a stable energy balance under which human civilizations developed. Significant positive forcing began with the Industrial Revolution, as greenhouse gas concentrations rose due to fossil fuel combustion and land conversion.[241]
Planetary Boundary (PB)	Scientists have proposed a PB for total anthropogenic radiative forcing at +1.0 W/m^2, relative to pre-industrial levels. This threshold is based on the climate system's sensitivity to greenhouse gas forcing, observed responses of polar ice sheets to warming, and growing evidence of climate instability at forcing levels above +1.5 W/m^2.[1] Exceeding this boundary increases the risk of irreversible climate impacts and long-term system feedback loops.

FIGURE 18 - Disturbance of our planet's energy balance. This figure shows the global average of human-induced radiative forcing at the top of the atmosphere from 1750 to 2024.[242] The values were calculated using observational data and established climate models, based on methods from the IPCC. The green line marks the safe baseline (0.0 W/m^2), and the red line indicates the Planetary Boundary (+1.0 W/m^2).

Key takeaway: *Human activities have significantly increased net radiative forcing to three times the safe limit, exerting a persistent warming influence on the Earth system and pushing well beyond the safe threshold.*

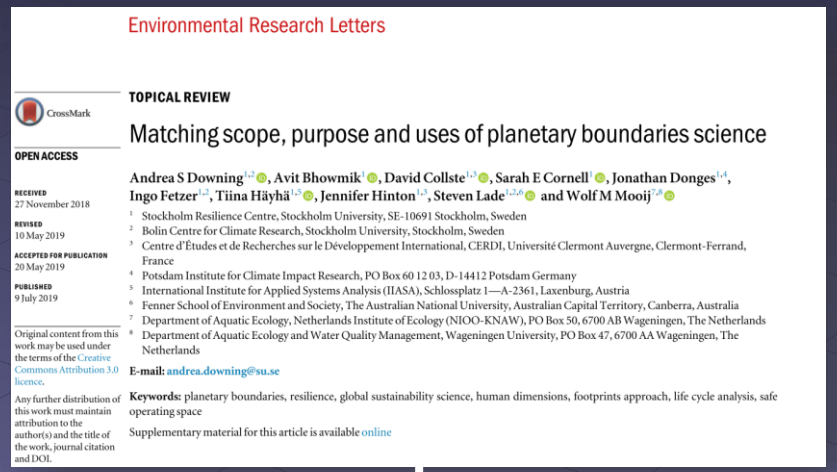
Critiques du concept dans le milieu académique

Littérature scientifique

Critiques constructives

- Choix de processus
- Choix des variables considérées non représentatives 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 l'équité ou le bien-être
- Le choix de la représentation et des couleurs n'est pas rigoureux
- …

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



Environmental Research Letters

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TOPICAL REVIEW

Matching scope, purpose and uses of planetary boundaries science

Andrea S Downing[1,2], Avit Bhowmik[1], David Collste[1,3], Sarah E Cornell[1], Jonathan Donges[1,4], Ingo Fetzer[1,2], Tiina Häyhä[1,5], Jennifer Hinton[1,3], Steven Lade[1,2,6] and Wolf M Mooij[7,8]

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3 Centre d'Études et de Recherches sur le Développement International, CERDI, Université Clermont Auvergne, Clermont-Ferrand, France
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Downing al. 2019, ERL

120 commentaires autour du concept

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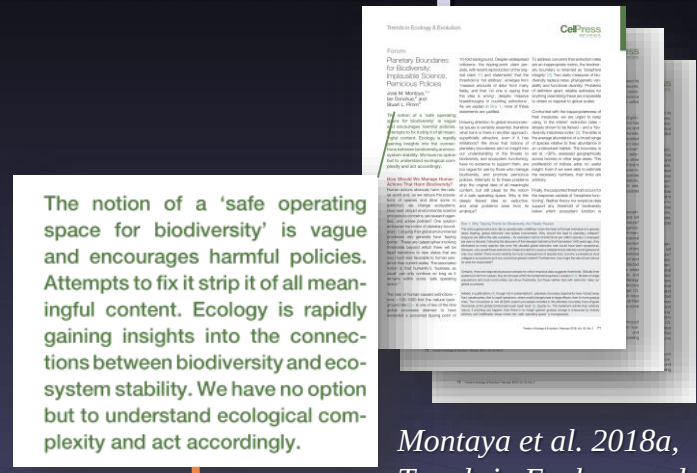
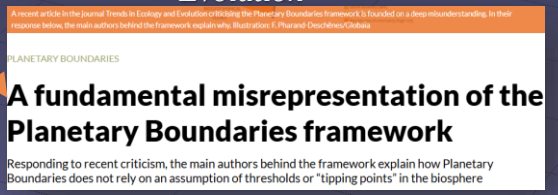
Critiques anti-PB

- Il n'y a beaucoup d'arbitraire
- Consortium d'expert biaisé – géosciences de pays occidentaux
- 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 boites 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)
- Impérialisme des STS sur les SHS


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 recent article in the journal Trends in Ecology and Evolution criticizing the Planetary Boundaries framework is founded on a deep misunderstanding. In their response below, the main authors behind the framework explain why. Illustration: F. Pharand-Deschênes/Globaia

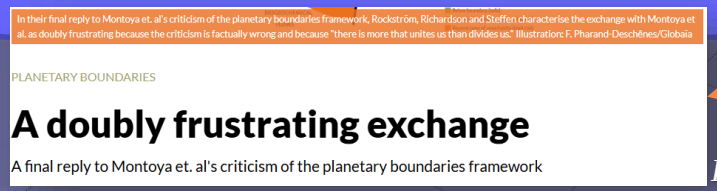
PLANETARY BOUNDARIES

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


In their final reply to Montoya et. al's criticism of the planetary boundaries framework, Rockström, Richardson and Steffen characterise 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." Illustration: F. Pharand-Deschênes/Globaia

PLANETARY BOUNDARIES

A doubly frustrating exchange

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

Rockström et al. 2018b

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- Ignore les initiatives communautaires dans lequel il y a une vraie construction de consensus scientifique et une interaction avec les acteurs (IPBES)
- Impérialisme des STS sur les SHS

Réseaux sociaux/couloirs

Ressentis/Commentaires

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- …

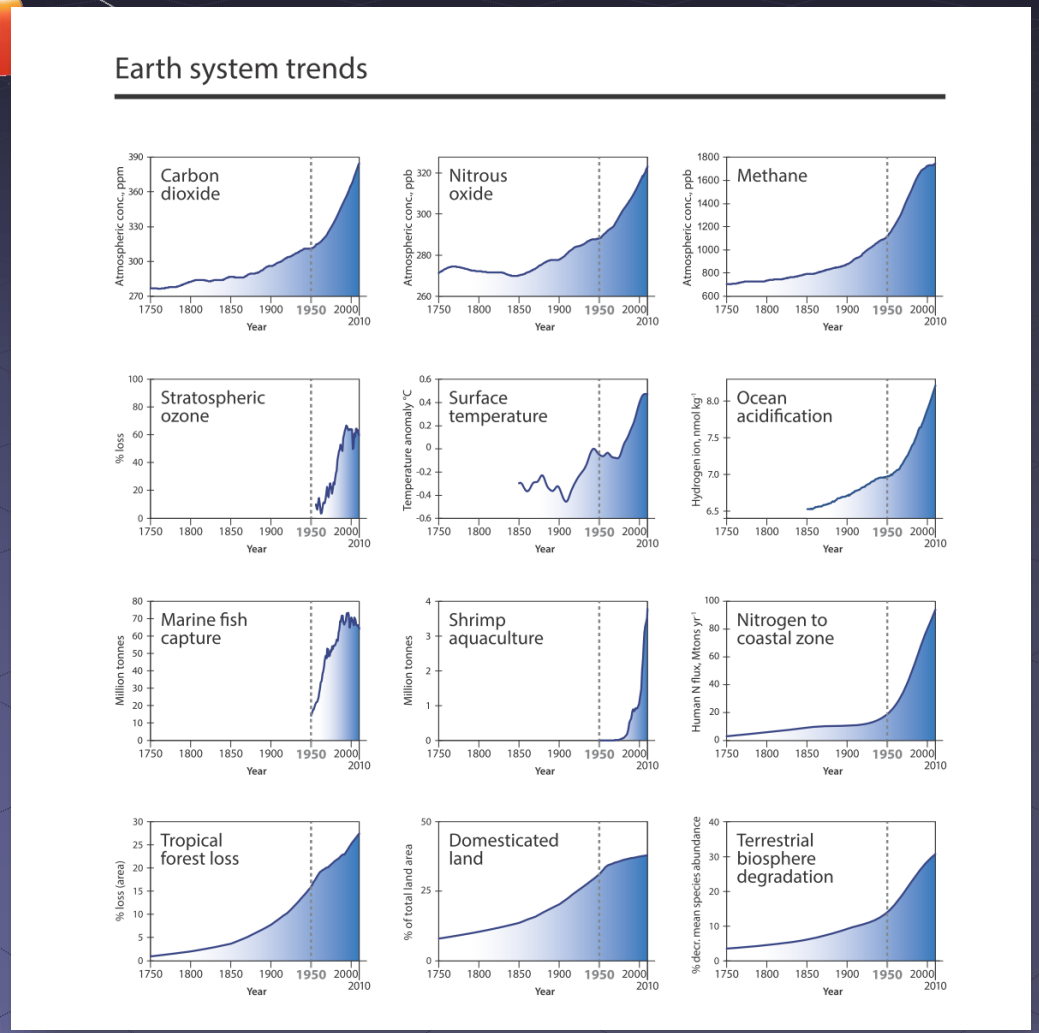
+

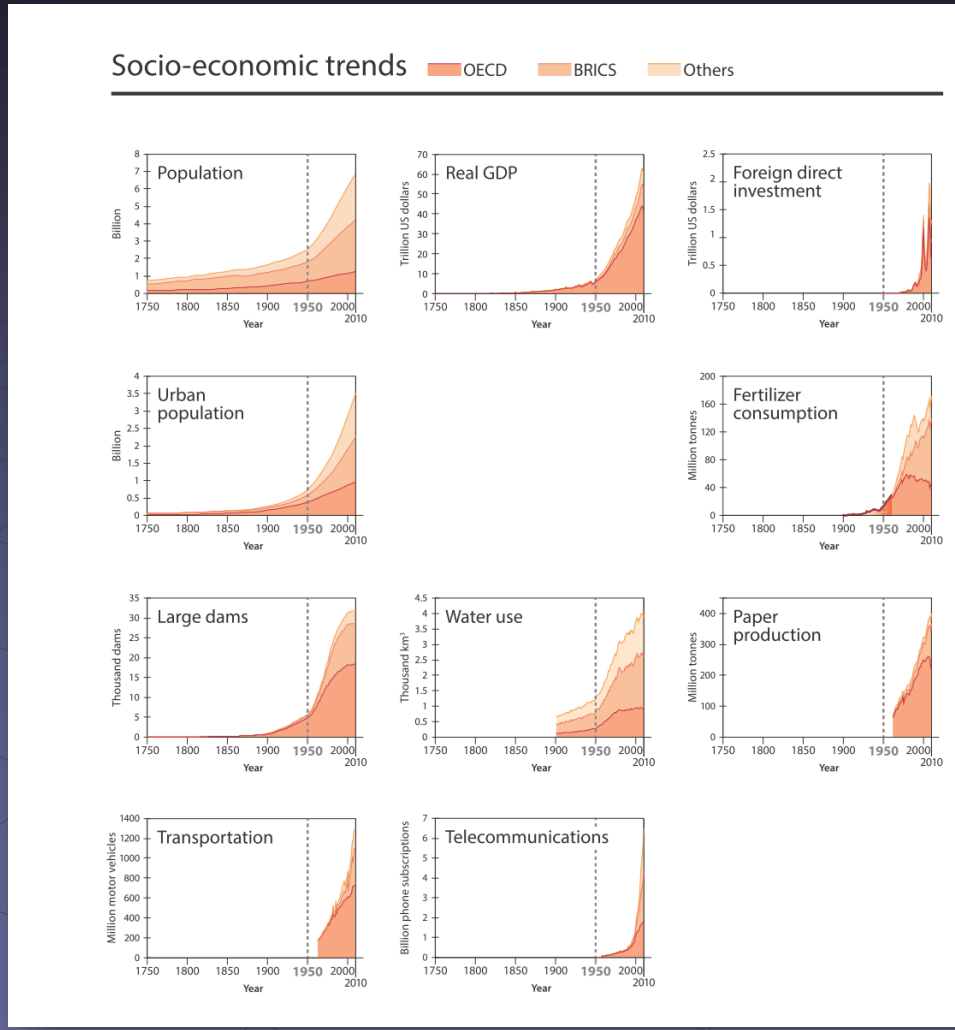
- Consortium fermé
- Auto-citation, auto-promotion
- Principalement un outil de comm'
- La définition de seuil est contre-productif pour l'action
- Dépolitisation de la situation environnementale

Au-delà du débat?

The trajectory of the Anthropocene: The Great Acceleration

Steffen et al. 2015, The Anthropocene review

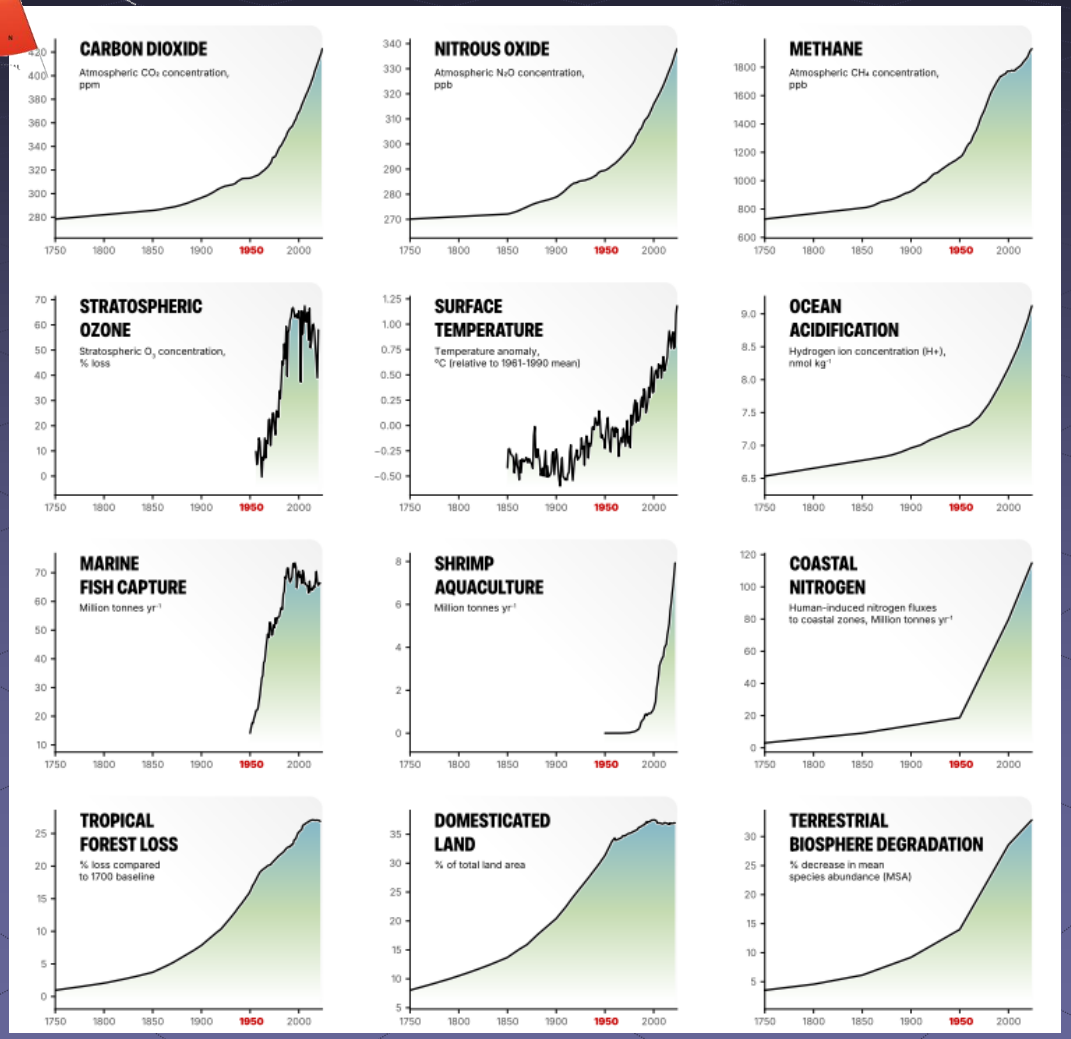


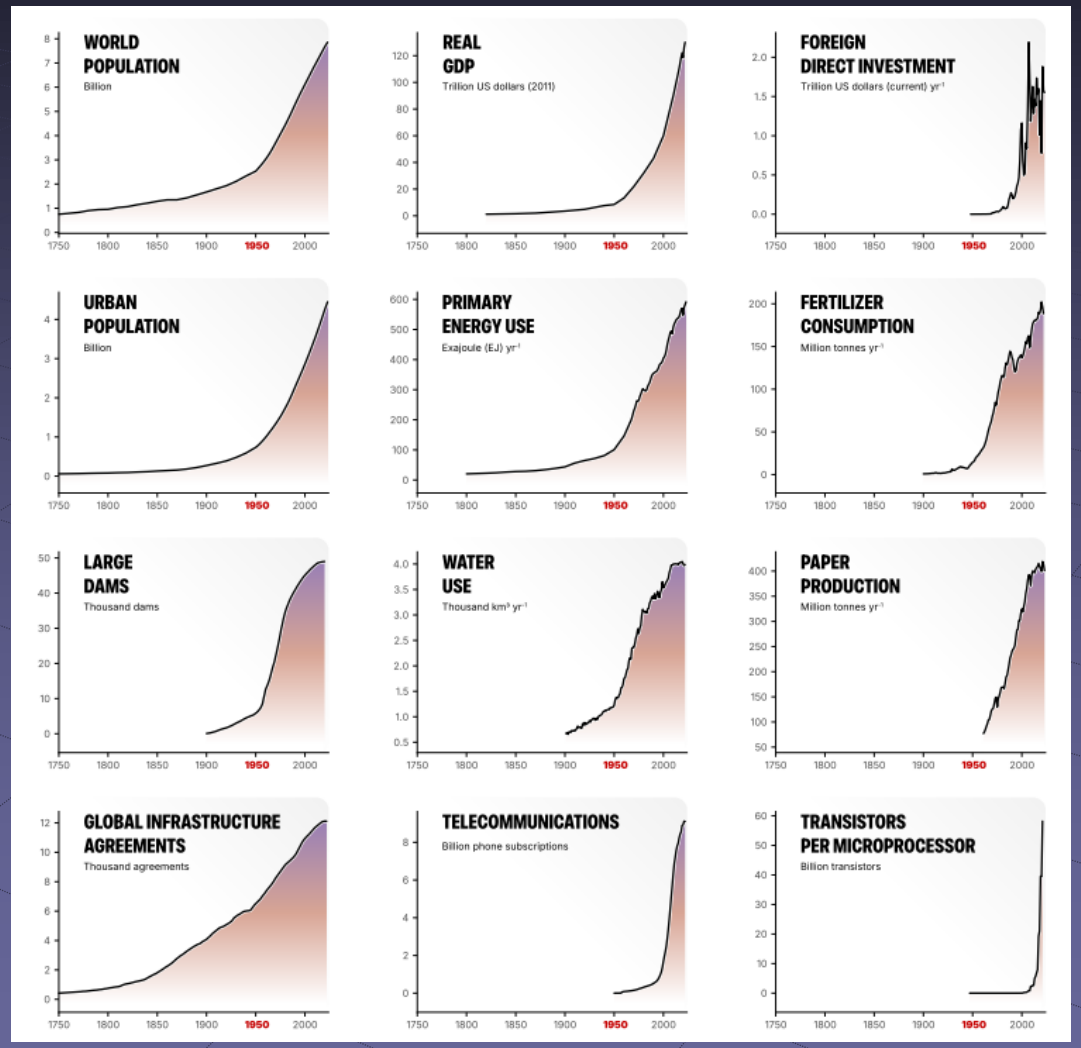


Au-delà du débat?

The trajectory of the Anthropocene: The Great Acceleration

Planetary Health Ckeck, 2025



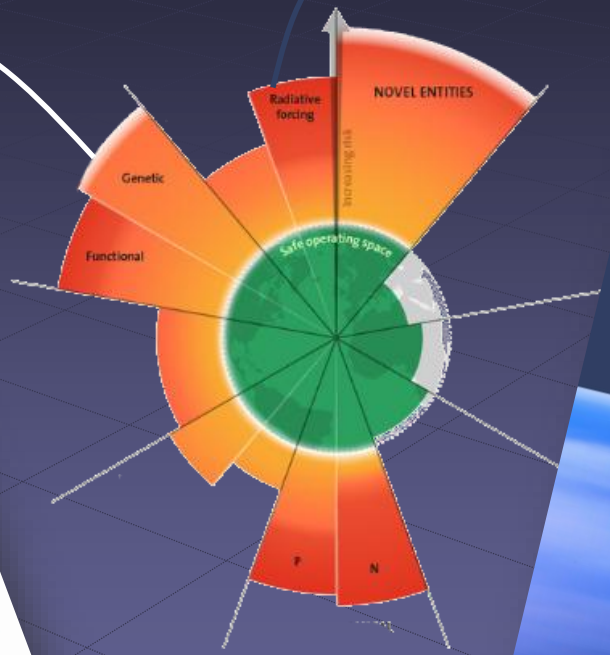


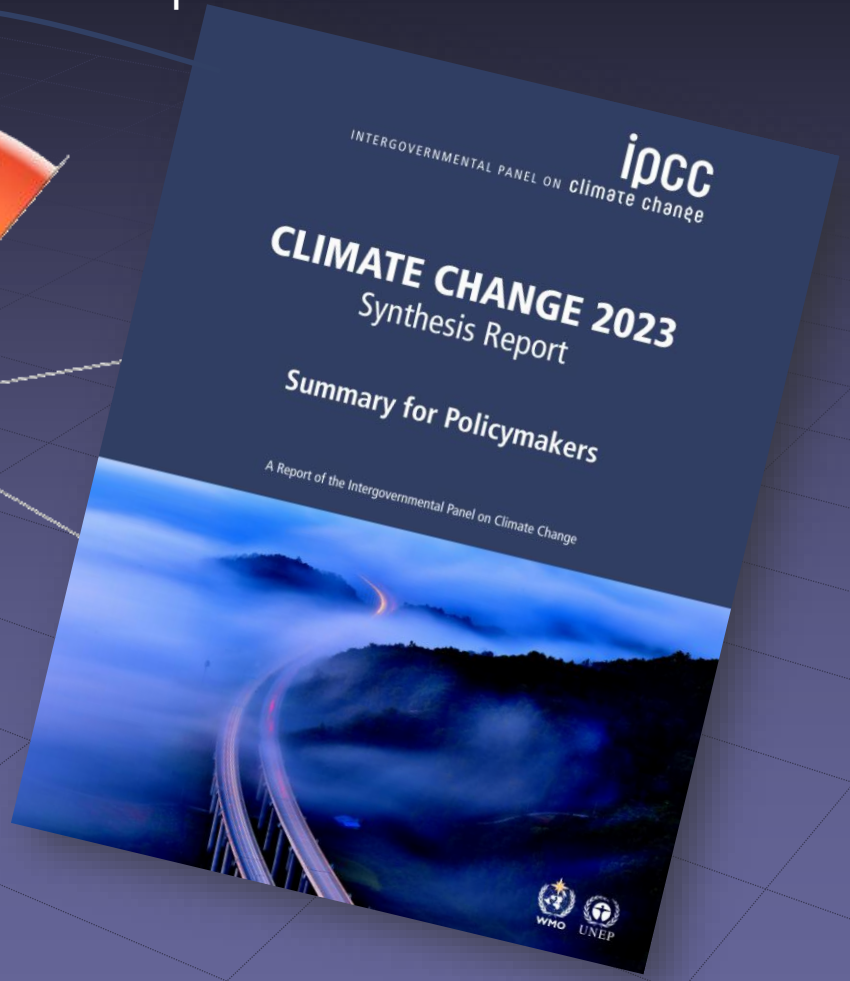
Au-delà du débat?

Pour l'analyse exhaustive et approfondie des processus

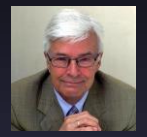
Des communautés plus larges et organisées:

→ état de l'art complet et approfondi de la situation de certaines composantes



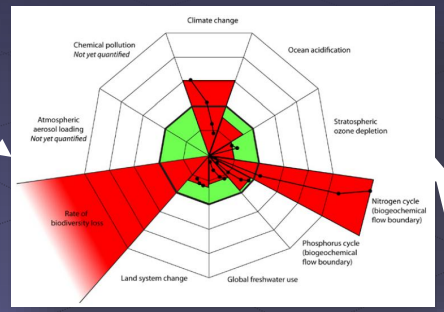


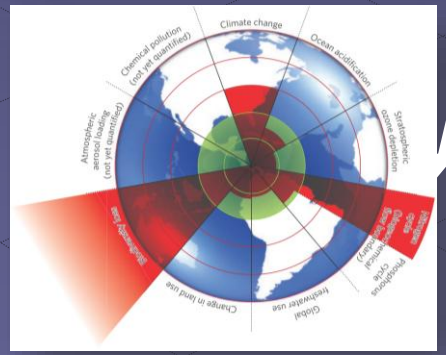
Un outil de communication



"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



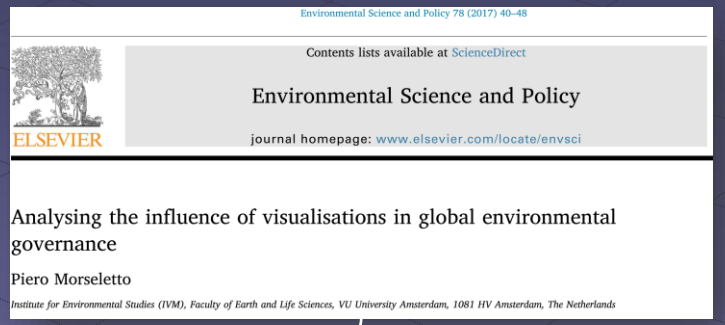


Rockström et al. 2009b

nature

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

Understandable
Meaningful
Engaging



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Analysing the influence of visualisations in global environmental governance

Piero Morseletto

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https://blog.duncangeere.com/a-dashboard-for-planet-earth-2/

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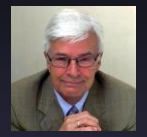

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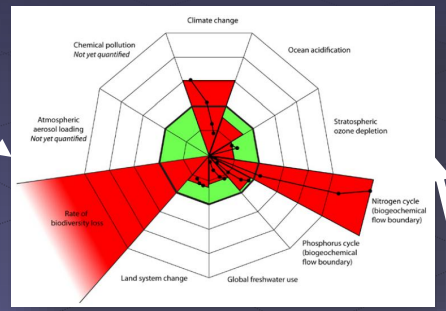
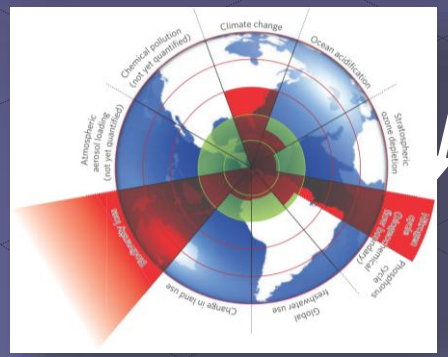




Rockström et al. 2009b

Impact immédiat

Médiatique
- ONG
- Journaux
- Médias en ligne

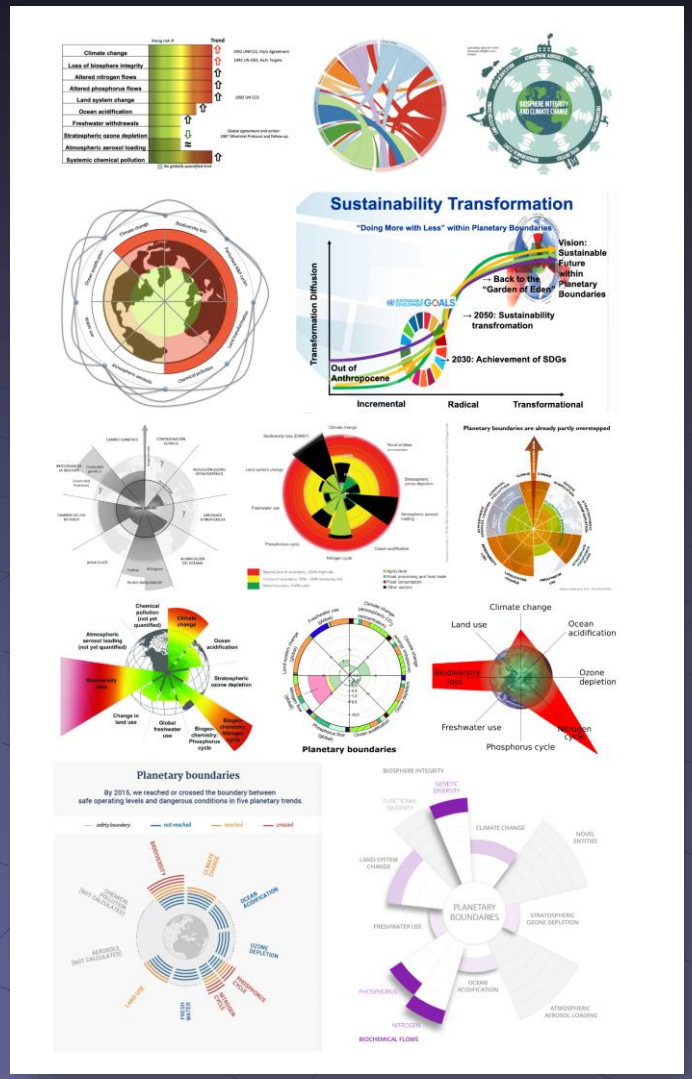
Académique
- Commentaires (>120 publications)
- Citations (>8800 citations)

nature

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

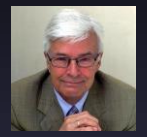
Understandable
Meaningful
Engaging

Google Image
« Planetary boundaries »



https://blog.duncangeere.com/a-dashboard-for-planet-earth-2/

Un outil de communication



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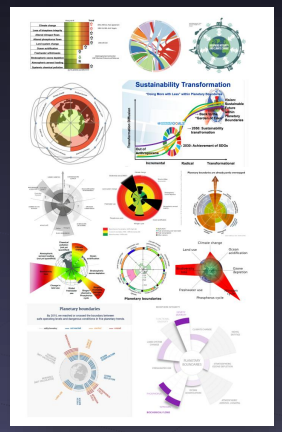

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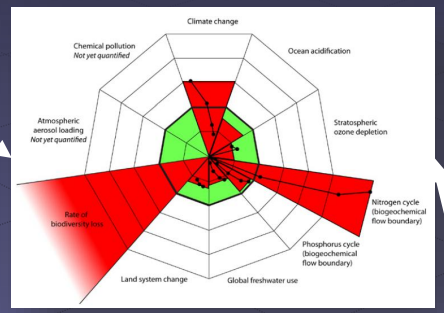

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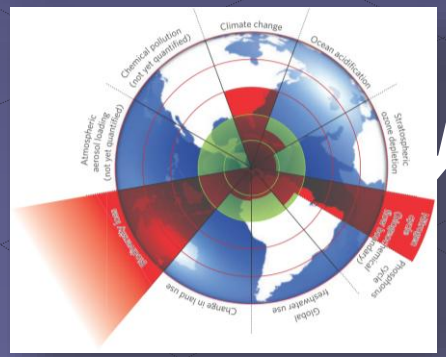
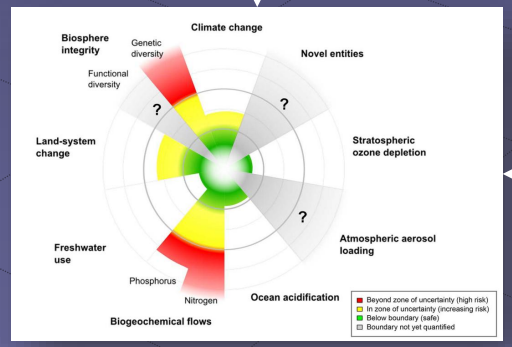
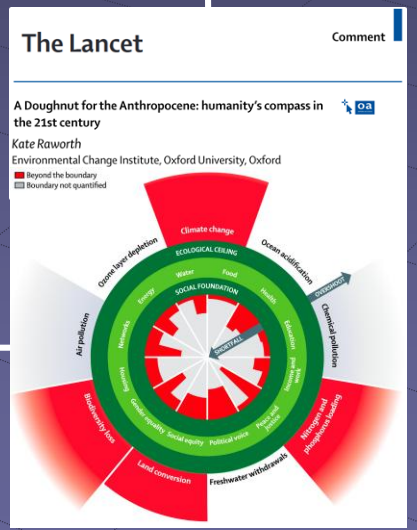


Rockström et al. 2009b



Steffen et al. 2015



Raworth 2017

https://blog.duncangeere.com/a-dashboard-for-planet-earth-2/

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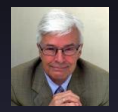


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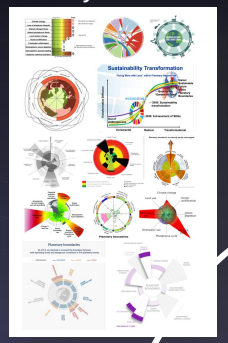

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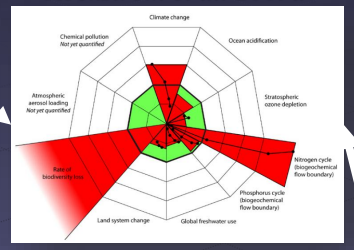

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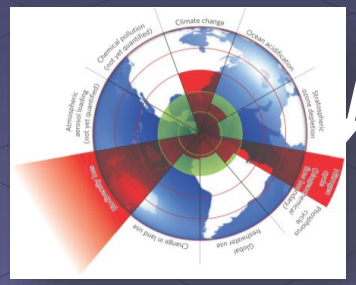
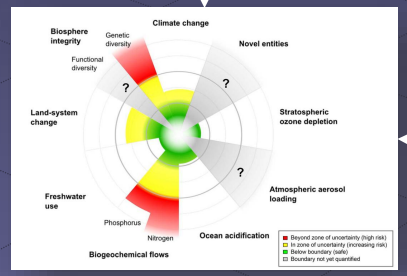


Rockström et al. 2009b



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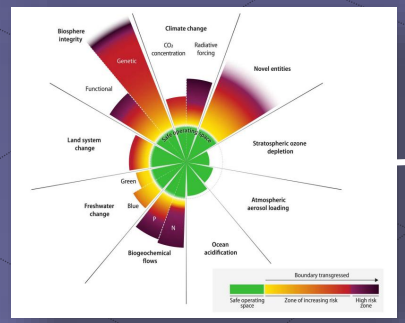
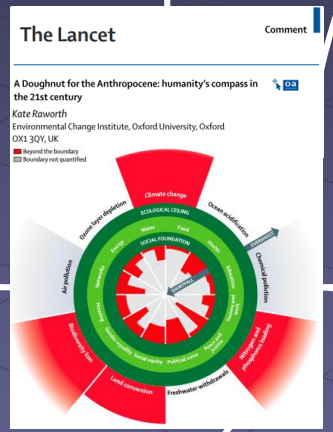


Richardson et al. 2023



Raworth 2017

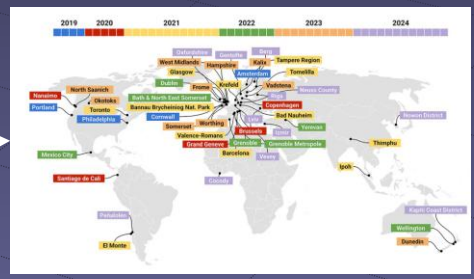
Intégration socio-économique

Wedding cake

https://www.stockholmresilience.org/research/research-news/2016-06-14-the-sdgs-wedding-cake.html

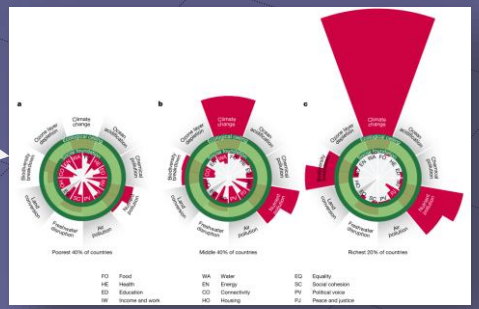
Safe and just space

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



Gvercha and Vianello, 2025

Applications Régionales



Fanninng and Raworth, 2025

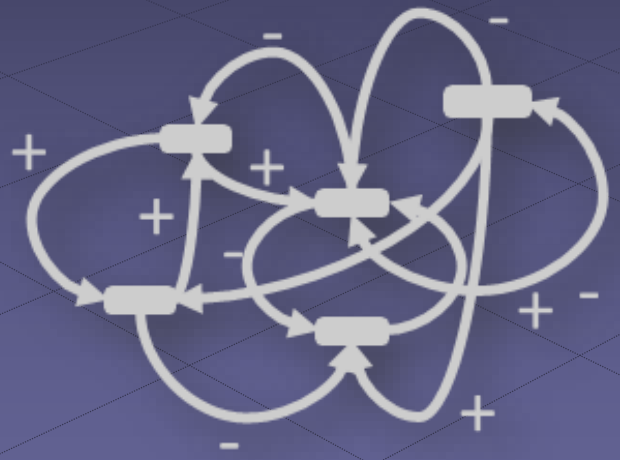
Inégalités Socio-environnementales

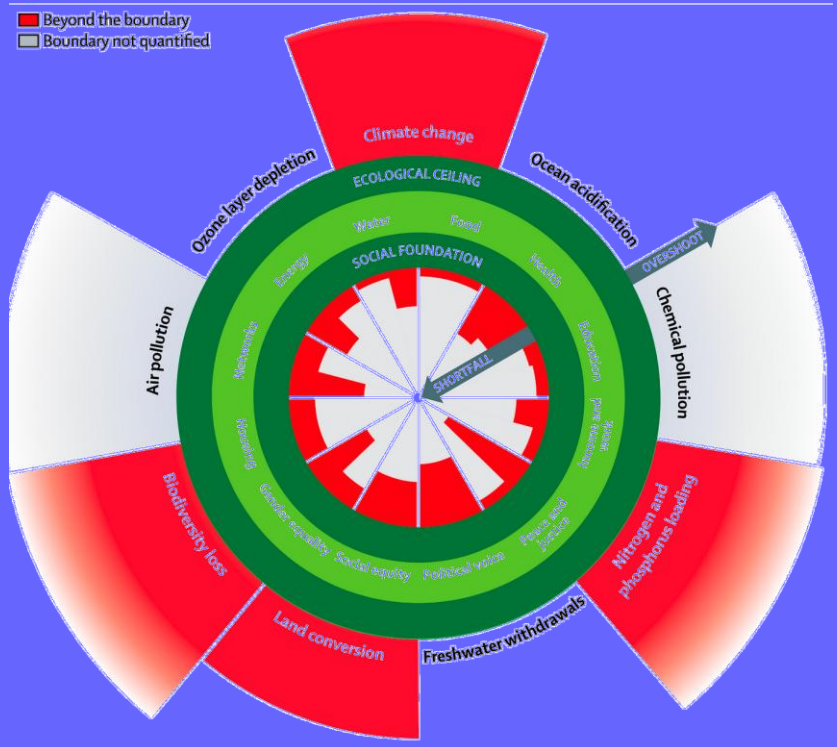
https://blog.duncangeere.com/a-dashboard-for-planet-earth-2/

Quelle utilisation du concept?

Un guide qualitatif pour fournir un cadre de réflexion systémique

Proposer des solutions à des problèmes socio-environnementaux





- Approche systémique
- Equité et justice socio-environnementale

Scénariser des futurs désirables

Quelle utilisation du concept?

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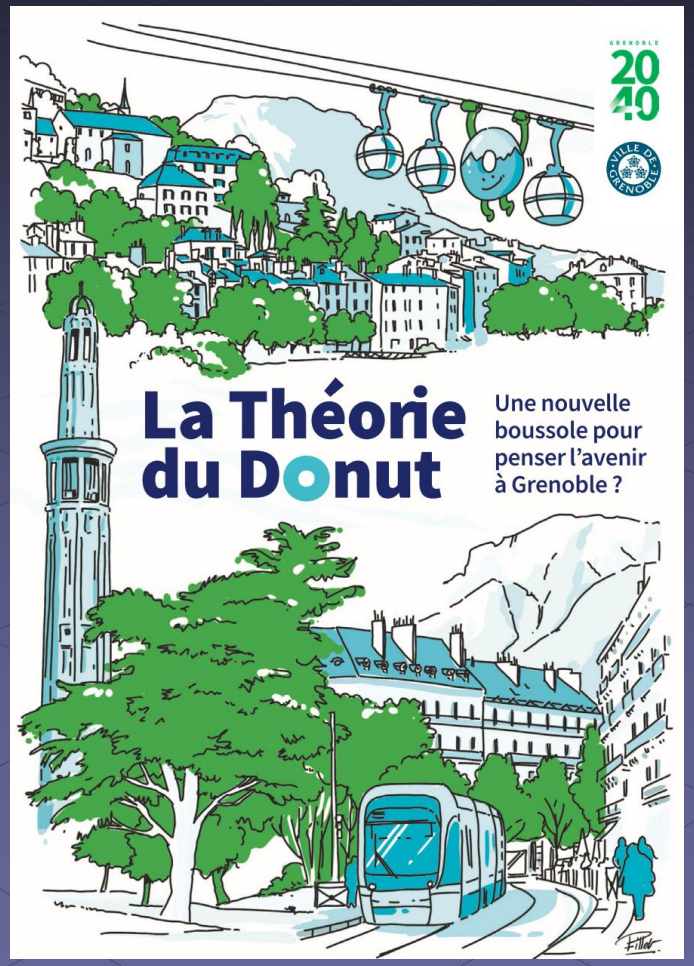

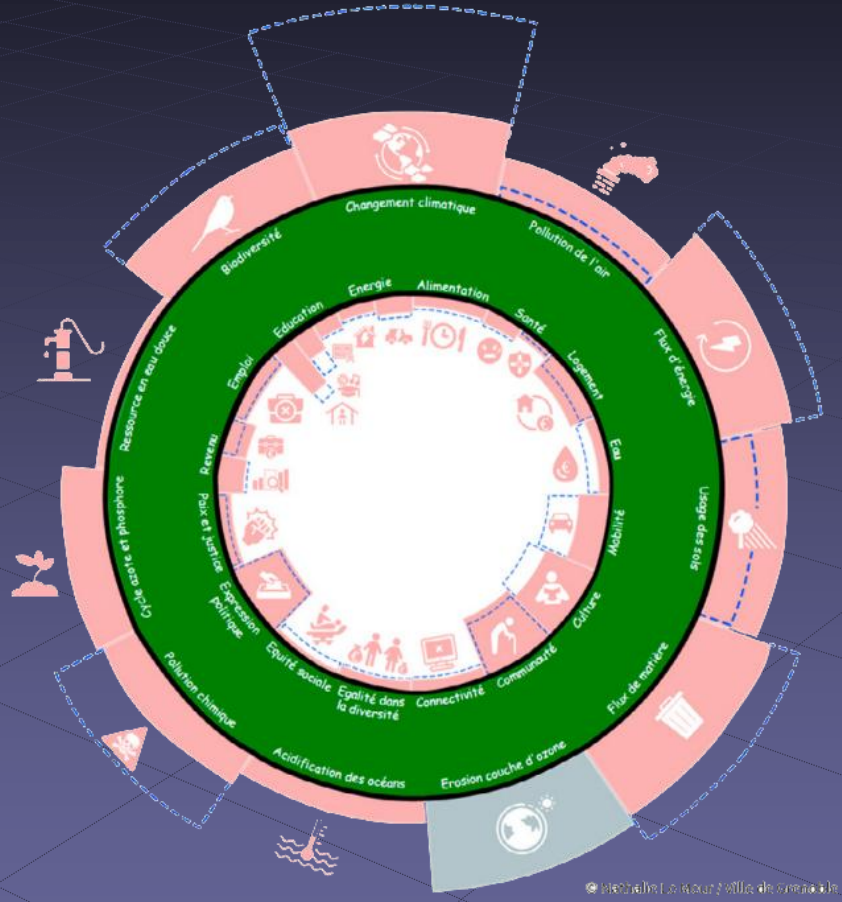

Scénariser des futurs désirables

Analyse quantitative contestable concernant les limites…
Boussole pour penser l'avenir socio-environnemental plus pertinent…

?

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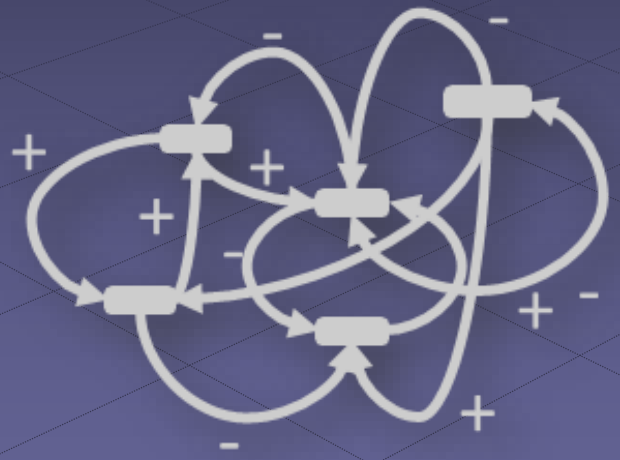

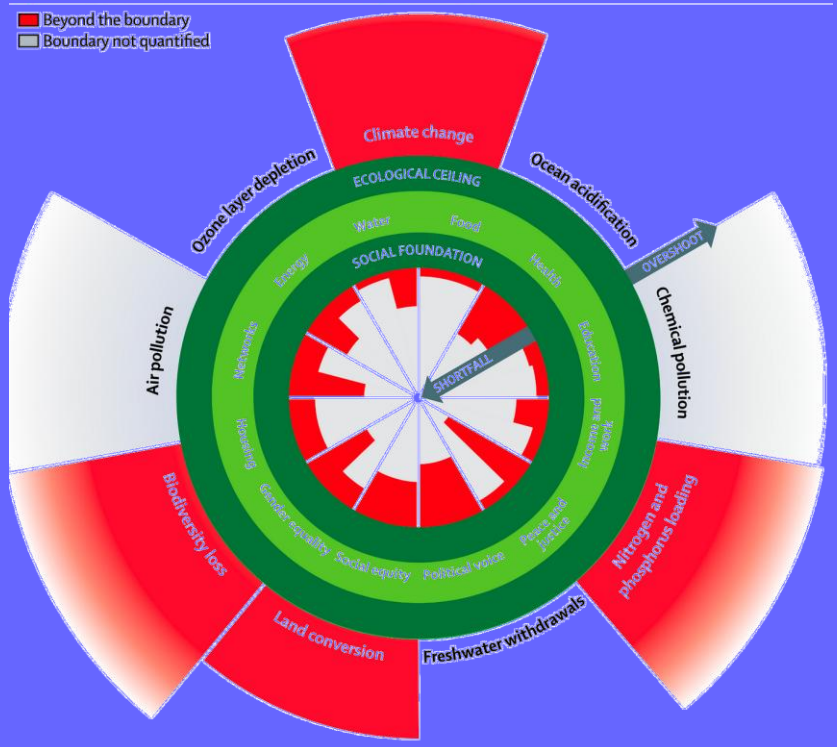

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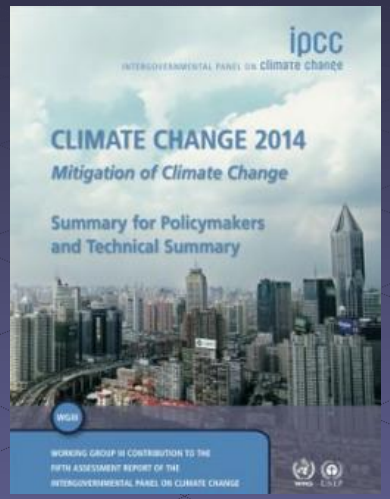
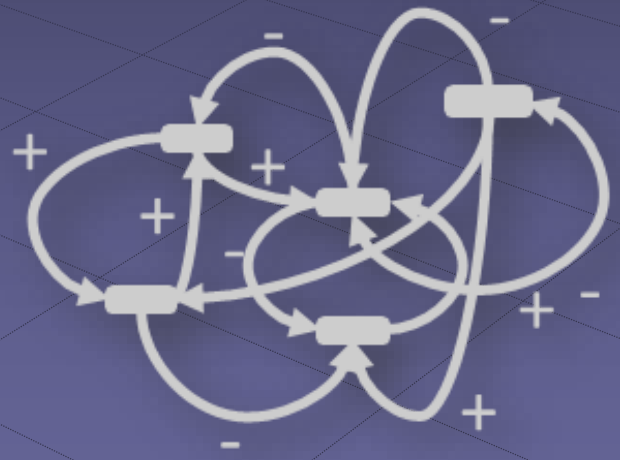
Atténuation



Proposer des solutions à des problèmes socio-environnementaux

Adaptation



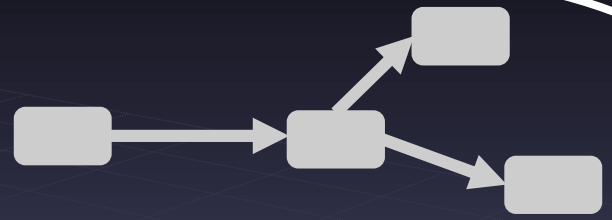
Malatténuation

- Lien thématique
- Approche systémique

Maladaptation

Quelle utilisation du concept?

Pensée en silo



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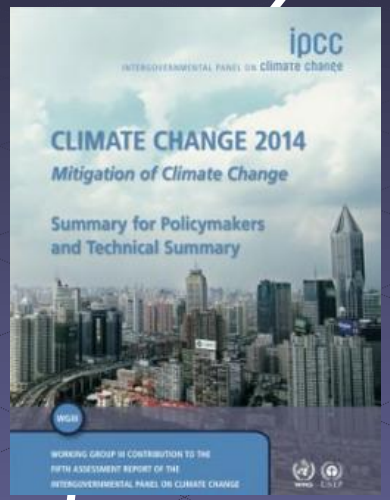

Malatténuation

Proposer des solutions à des problèmes socio-environnementaux

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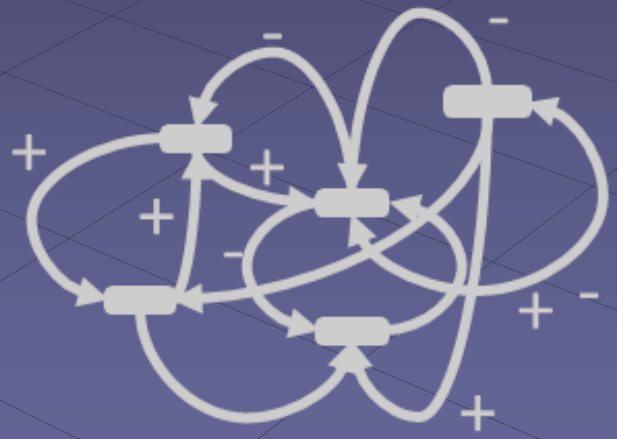

Adaptation

Maladaptation

- Lien thématique
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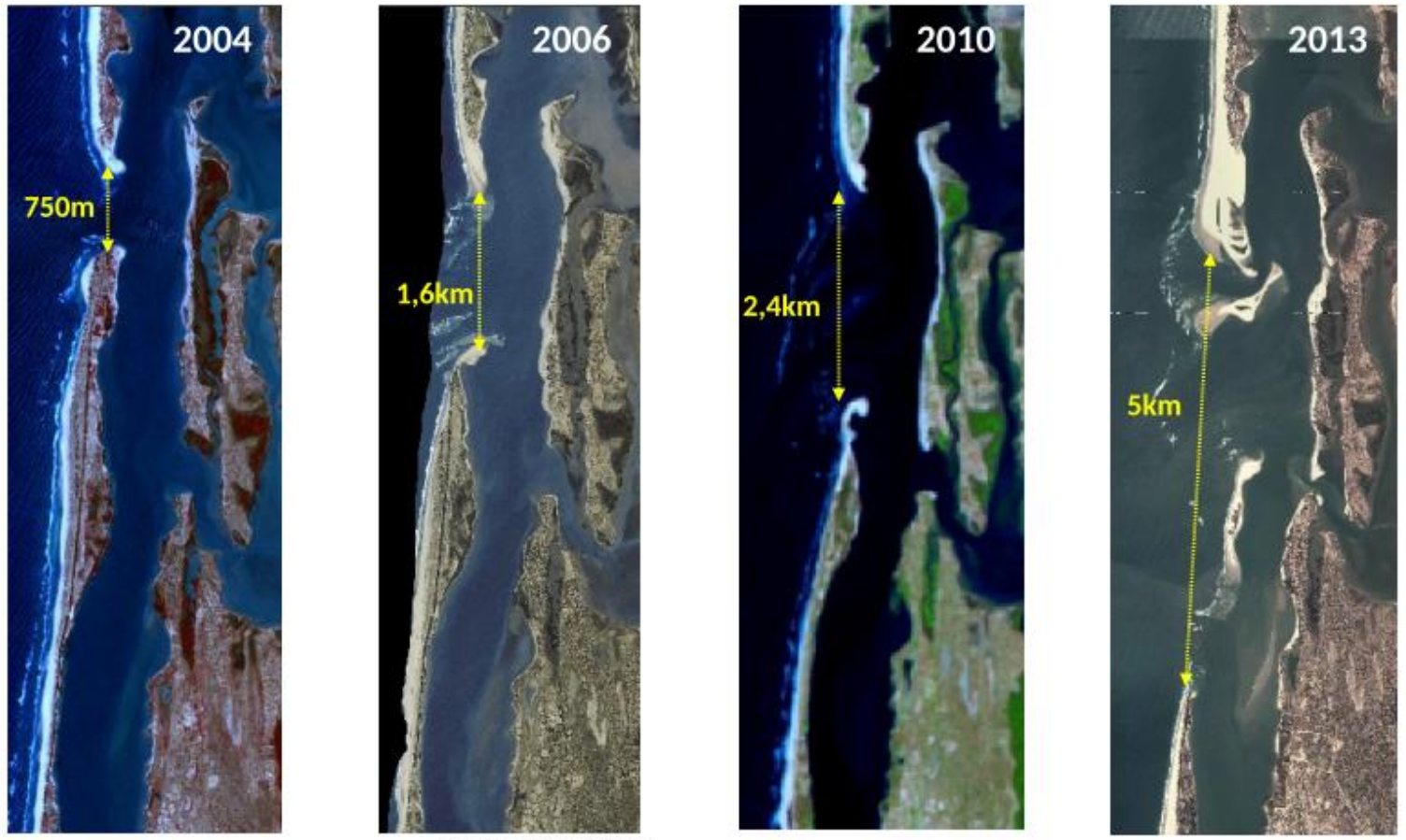
Approche en silo

Fleuve Sénégal
La brèche de Saint Louis

Approche en silo



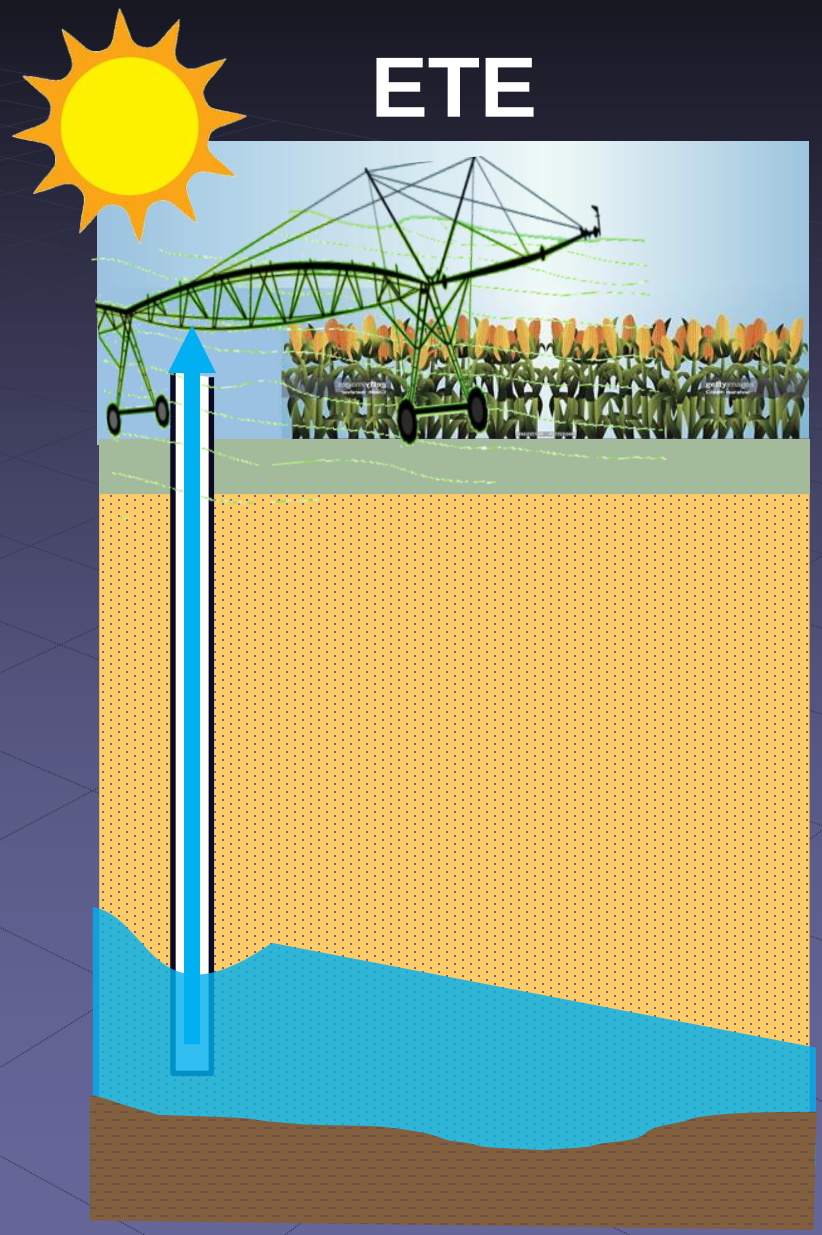
Source: DIENG (2013)

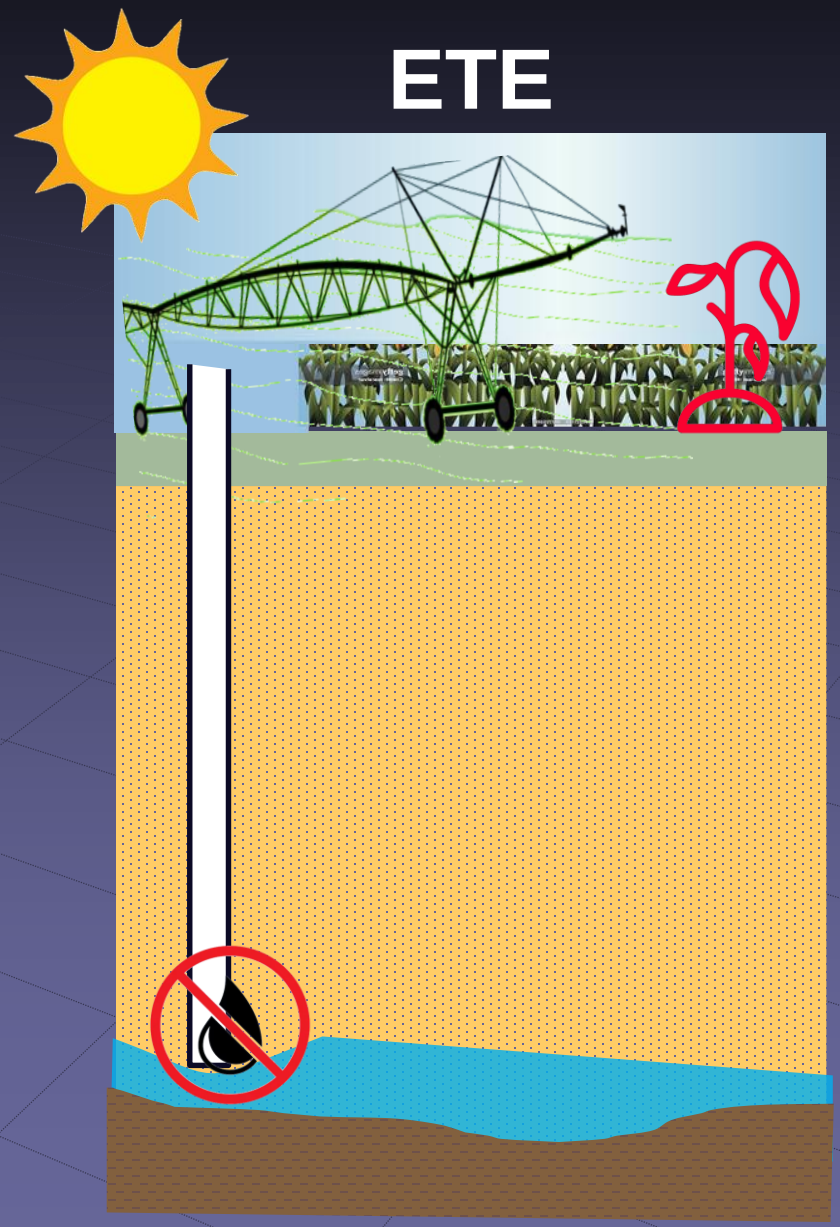
Fleuve Sénégal
La brèche de Saint Louis

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

Approche en silo

Approche en silo



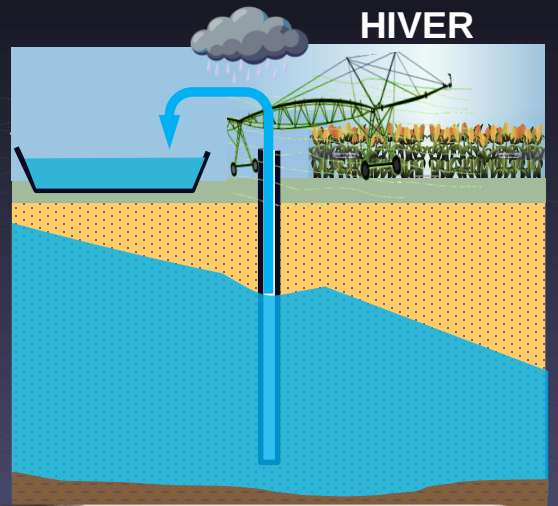


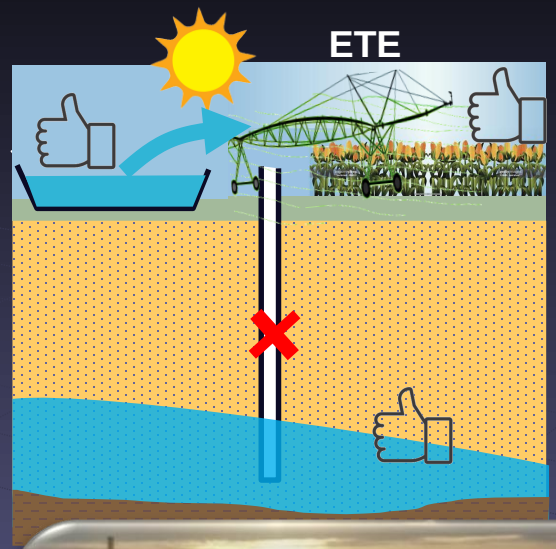
Approche en silo

HIVER

ETE

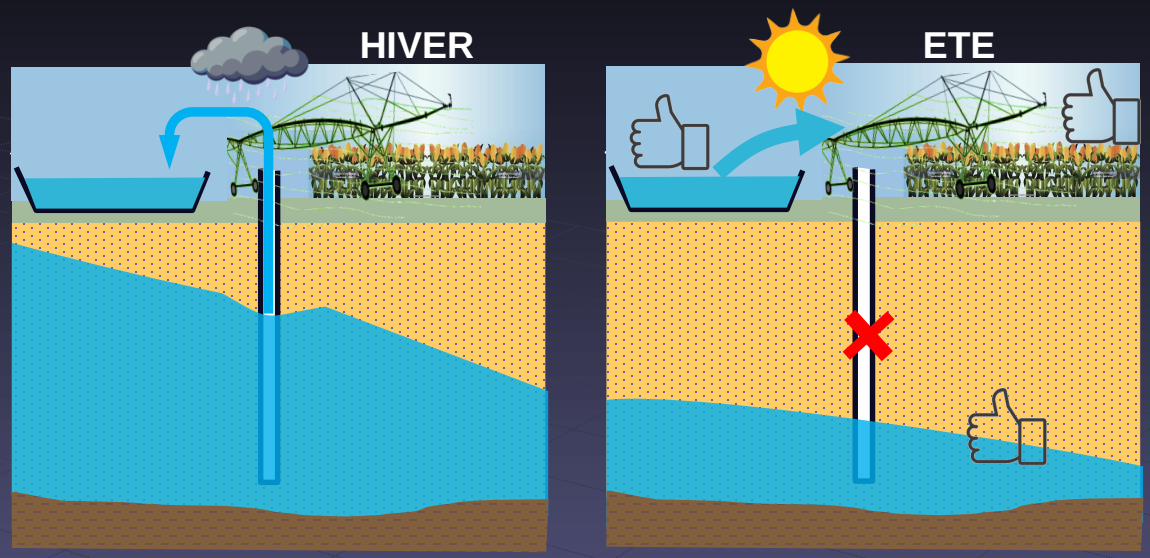
Approche en silo





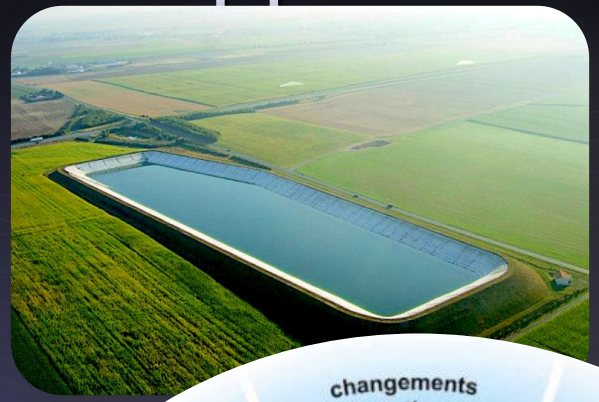
Pourquoi tant de haine ?

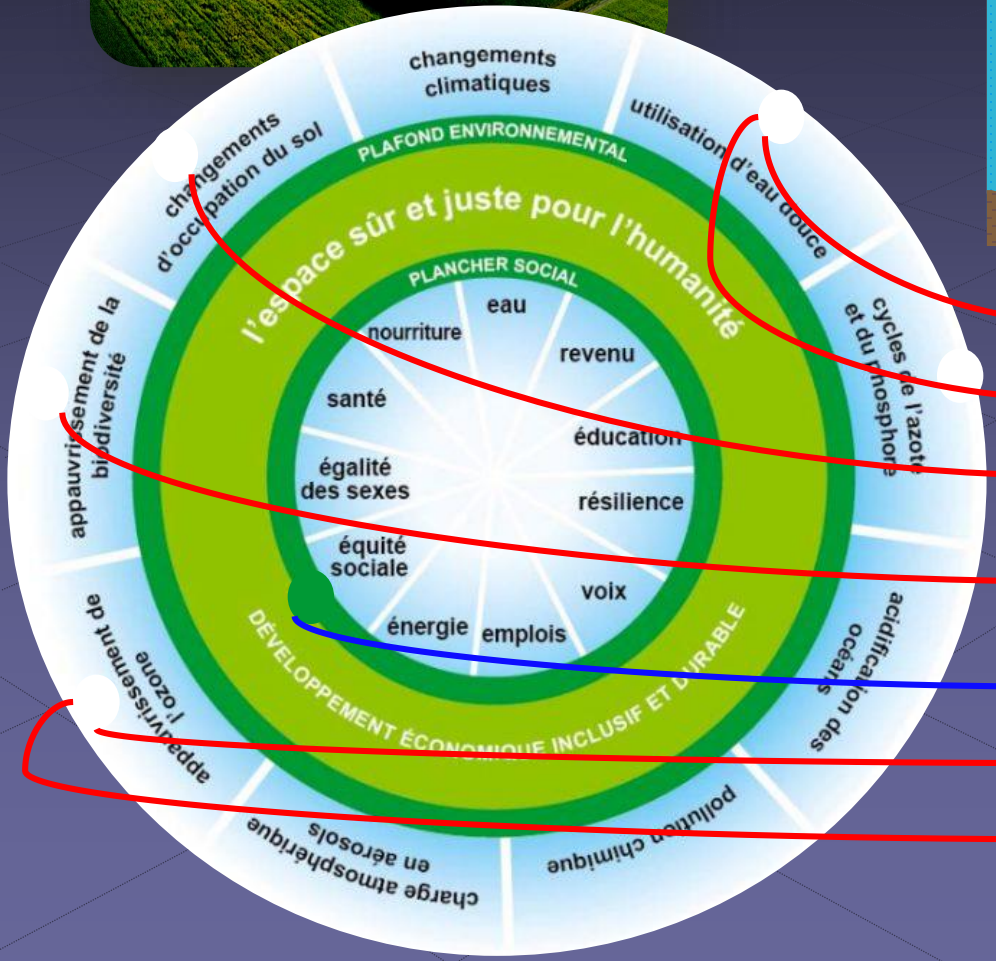
Approche en silo VS Démarche systémique

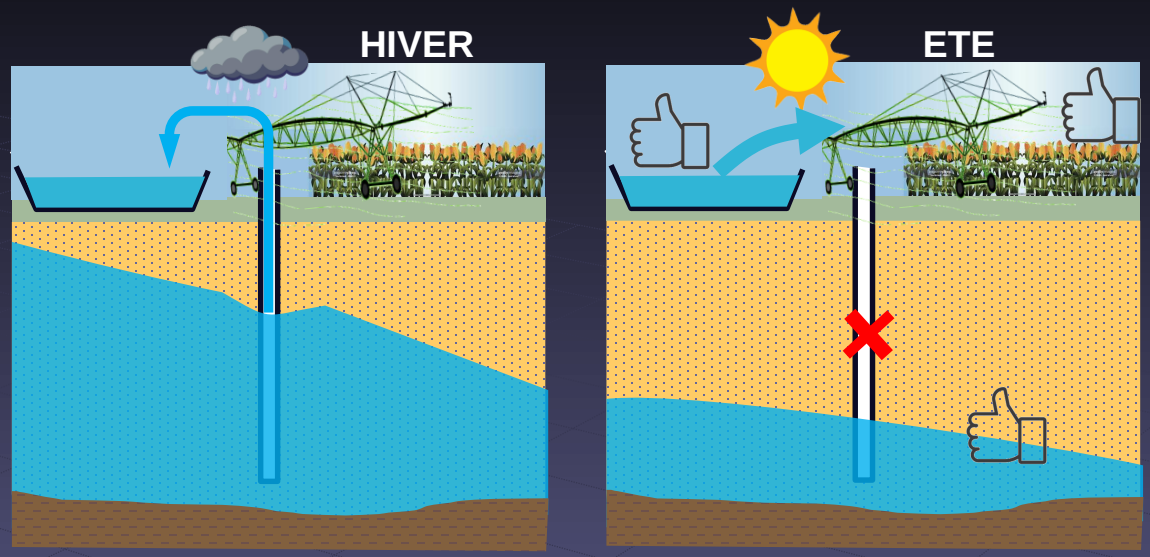


- Evaporation vs stockage souterrain
- Eau souterraine hivernale alimente les rivières
- Dégradation des sols
- Eau souterraine hivernale nécessaire à écosystème de rivières et océaniques
- Privatisation d’un bien commun
- Maintien d’un système agricole intensif polluant
- Dégradation de la qualité des eaux

Approche en silo VS Démarche systémique







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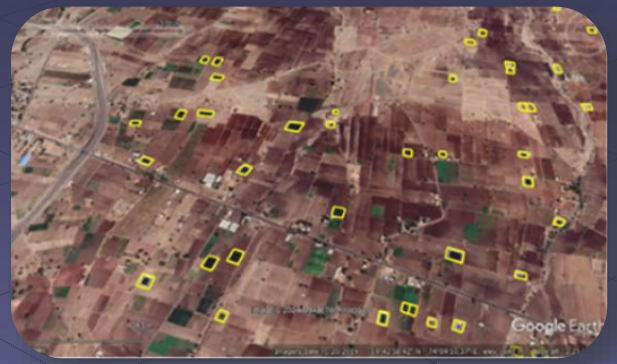
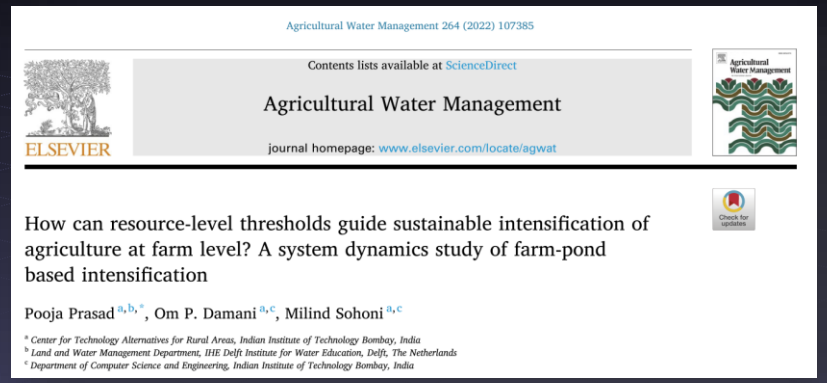


Autres
effets systémiques
Exemple en Inde



Agricultural Water Management 264 (2022) 107385

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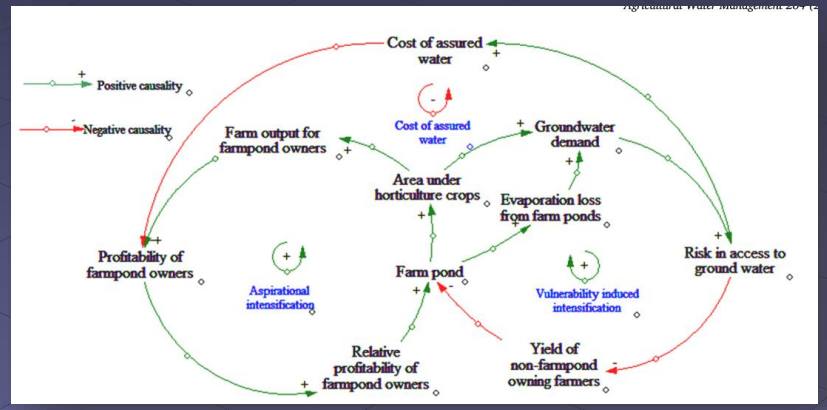
How can resource-level thresholds guide sustainable intensification of agriculture at farm level? A system dynamics study of farm-pond based intensification

Pooja Prasad [a,b,*], Om P. Damani [a,c], Milind Sohoni [a,c]

[a] Center for Technology Alternatives for Rural Areas, Indian Institute of Technology Bombay, India
[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

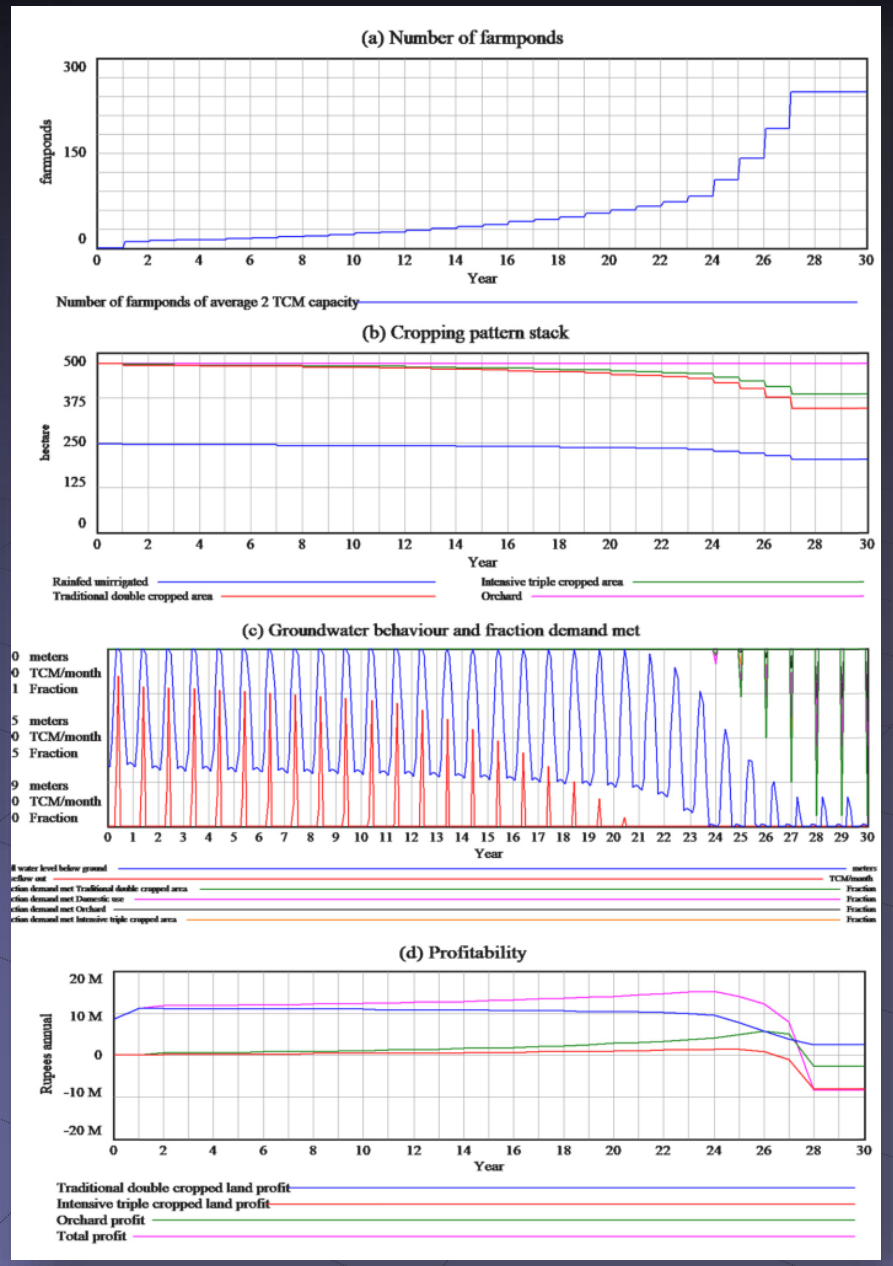
Prasad et al. 2022, Agriculture & Water management



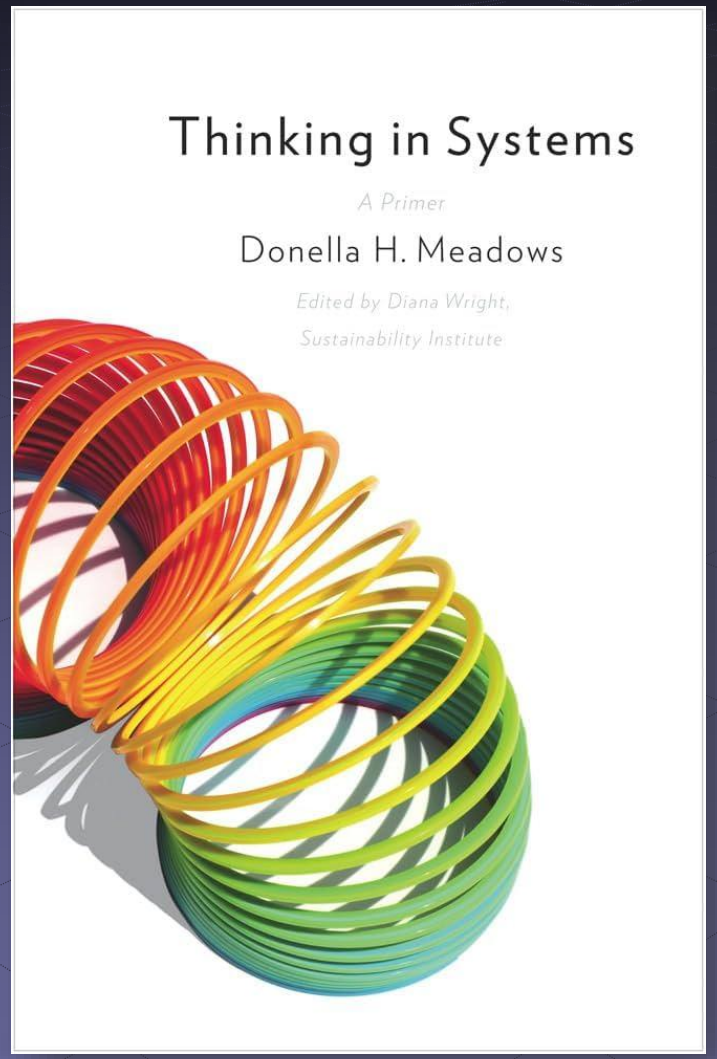
Scénario sans changement climatique

Archétype systémique

« Tragédie des communs »



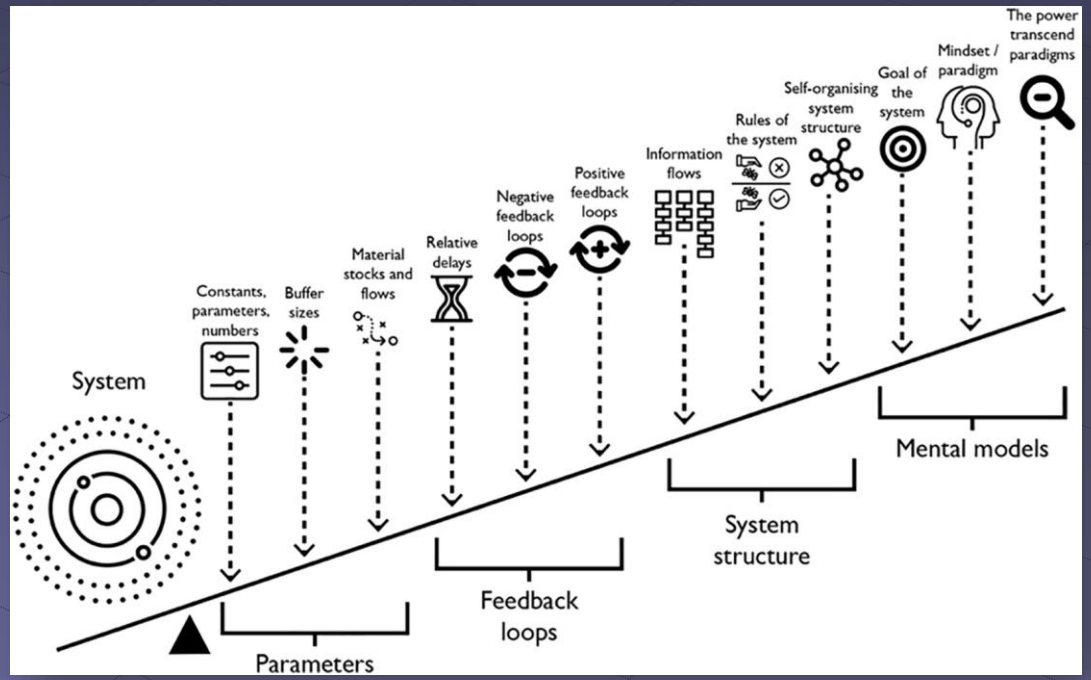
Démarche systémique



→ Archétype systémique

→ Leviers systémiques

Comprendre pour agir en connaissance de causes et de conséquences



Recommandation de lecture

- Biermann, F., and R. E. Kim, 2020: The Boundaries of the Planetary Boundary Framework: A Critical Appraisal of Approaches to Define a “Safe Operating Space” for Humanity. *Annual Review of Environment and Resources*, **45**, 497–521, https://doi.org/10.1146/annurev-environ-012320-080337.
- Bunsen, J., M. Berger, and M. Finkbeiner, 2021: Planetary boundaries for water – A review. *Ecological Indicators*, **121**, 107022, https://doi.org/10.1016/j.ecolind.2020.107022.
- Fanning, A. L., and K. Raworth, 2025: Doughnut of social and planetary boundaries monitors a world out of balance. *Nature*, **646**, 47–56, https://doi.org/10.1038/s41586-025-09385-1.
- Gupta, J., and Coauthors, 2024: A just world on a safe planet: a Lancet Planetary Health–Earth Commission report on Earth-system boundaries, translations, and transformations. *The Lancet Planetary Health*, S2542519624000421, https://doi.org/10.1016/S2542-5196(24)00042-1.
- Lade, S. J., and Coauthors, 2019: Human impacts on planetary boundaries amplified by Earth system interactions. *Nat Sustain*, **3**, 119–128, https://doi.org/10.1038/s41893-019-0454-4.
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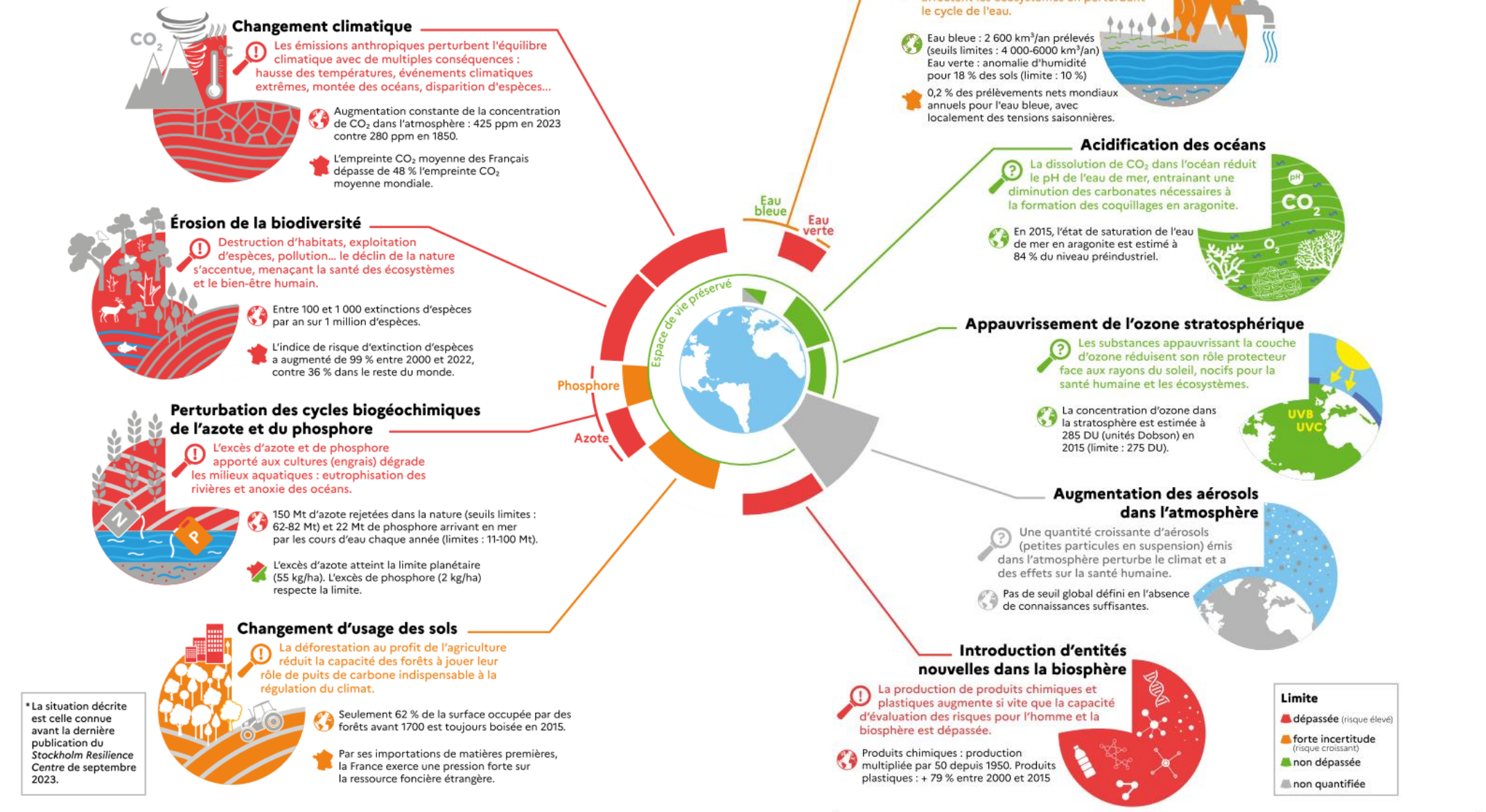
Les 9 limites planétaires*



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

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