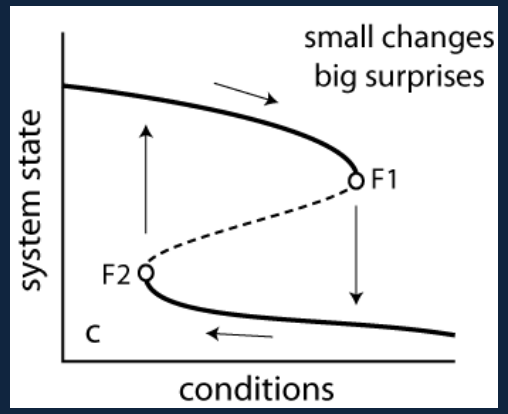
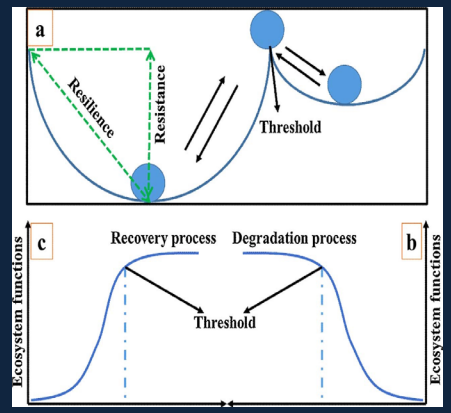
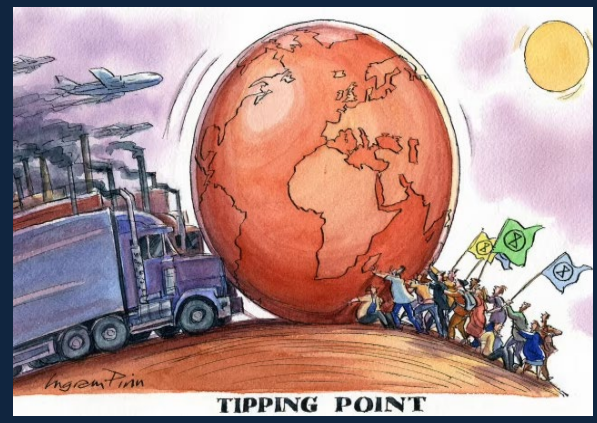
Tipping Points Workshop

a.k.a. – Critical Transitions, Thresholds, Regime Shifts, Transformations, Etc.







Purpose

- Provide an open forum to share and discuss research
- Identify Gaps and Opportunities for Research, Partnerships, and Collaborations
- To Engage in "Deep Dive" Topics and Discussions

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HTTP://CS3.MIT.EDU
/

Tipping Points Workshop

- **Welcome and Opening Remarks (Adam and Jen)**
- **Flash talks on "Tipping Points"**
    1) **Etienne Berthet, Postdoctoral Researcher, MIT CS3**
    2) **Angelo Gurgel, Principal Research Scientist, MIT CS3**
    3) **Jake Jacoby, Professor Emeritus, MIT**
- **Breakout Discussion Groups: ~30 minutes**
- **Reconvene for brief summaries from Breakout Groups**

Breakout 1: Adam Schlosser and Kevin Lin Yang
Breakout 2: Jen Morris and Chris Womack
Breakout 3: Etienne Berthet and Dominic White
Breakout 4: John Reilly and Angelo Gurgel

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Breakout Discussions

- Discussion Questions:
  - Q1: What are examples of “tipping points” in (and between) physical and social systems?
  - Q2: Is the “tipping point” concept relevant for organizing research?
  - Q3: How might research address tipping points (or alternative concepts)?
  - Q4: What topics would you like to see explored in follow-up workshops?

- For each Breakout Group:
  - Shared Google Doc
  - Put your thoughts down - even if you speak them!

- Please engage in lively discussion - thank you!

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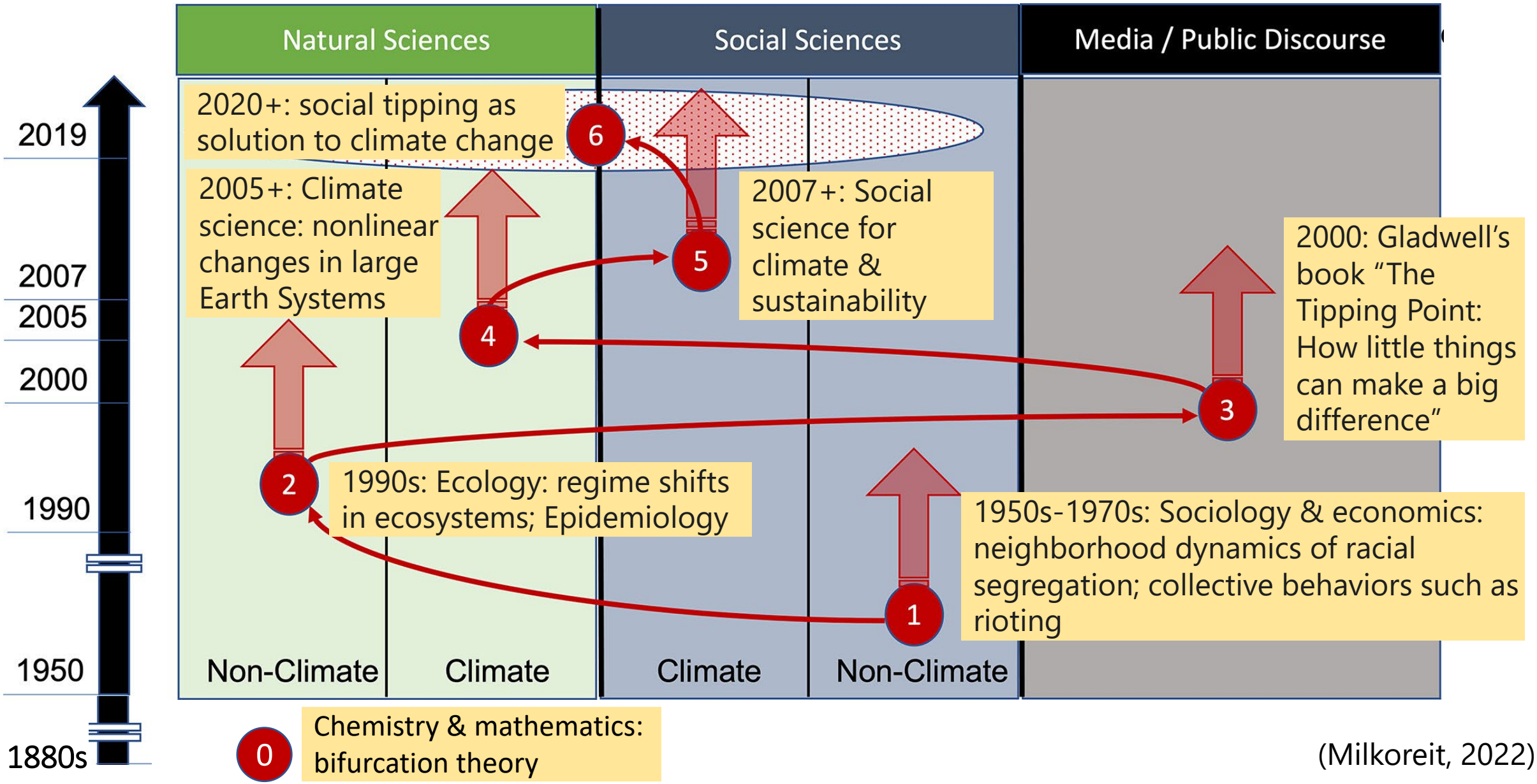
History of “tipping points”



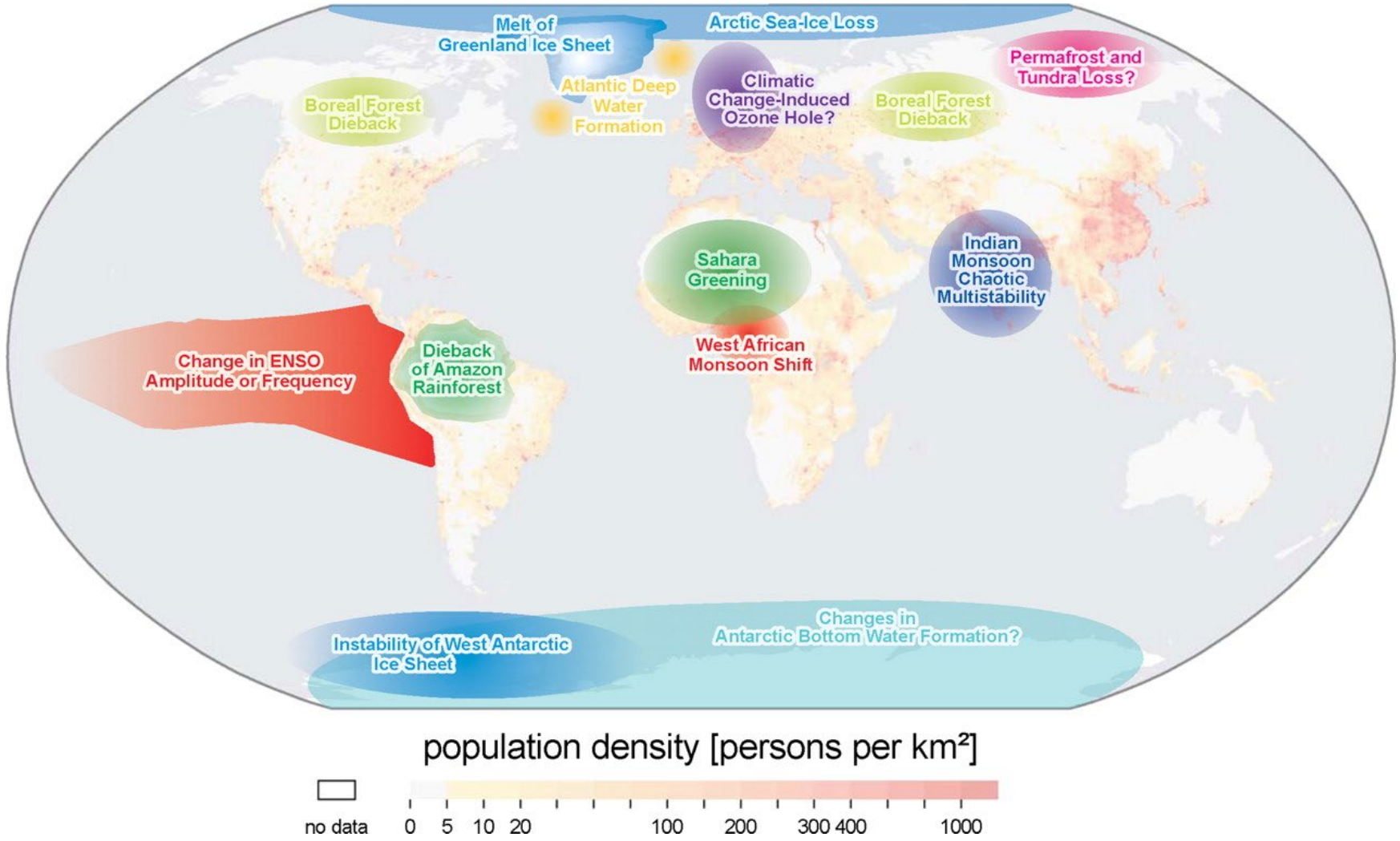
(Milkoreit, 2022)

Definitions of “Tipping Point”

- “Point at which a series of small changes or incidents becomes significant enough to cause a larger, more important change” (Oxford English Dictionary)
- “That magic moment when an idea, trend, or social behavior crosses a threshold, tips, and spreads like wildfire” (Malcolm Gladwell’s book *The Tipping Point: How little things can make a big difference,* 2000)
- “a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system.” (Lenton et al. 2008)
  - “A climate 'tipping point' occurs when a small change in forcing triggers a strongly nonlinear response in the internal dynamics of part of the climate system, qualitatively changing its future state” (Lenton, 2011)
  - “tipping elements”: large-scale components of the Earth system that may pass a tipping point

Map of potential policy-relevant tipping elements in the climate system (Lenton et al. 2008)

Many do not have convincingly established tipping points… but there may be potential for early warning



Definitions of “Tipping Point”

- “Social tipping point”: “nonlinear processes of transformative change in social systems” (Milkoreit et al., 2018)
  - Often desirable, offering potential solutions to pressing problems, like climate change
  - Could be intentionally induced—deliberately activated—rather than passively experienced
  - These two assumptions—desirability and intentionality—are risky→ curious degree of confidence in our collective ability to initiate and control rapid and radical change in social systems
  - We don’t know if “tipping behavior in a social system is conceptually equal or (partly) different than tipping processes in an ecological system. It remains unknown whether tipping points in natural systems, such as a lake or the climate, display the same underlying mechanisms as tipping points in social systems, such as in financial markets or political institutions.”

Literature Review 1960-2016 (Milkoreit et al., 2018)

- Examines temporal trends in terminology and identifies different definitions and their components

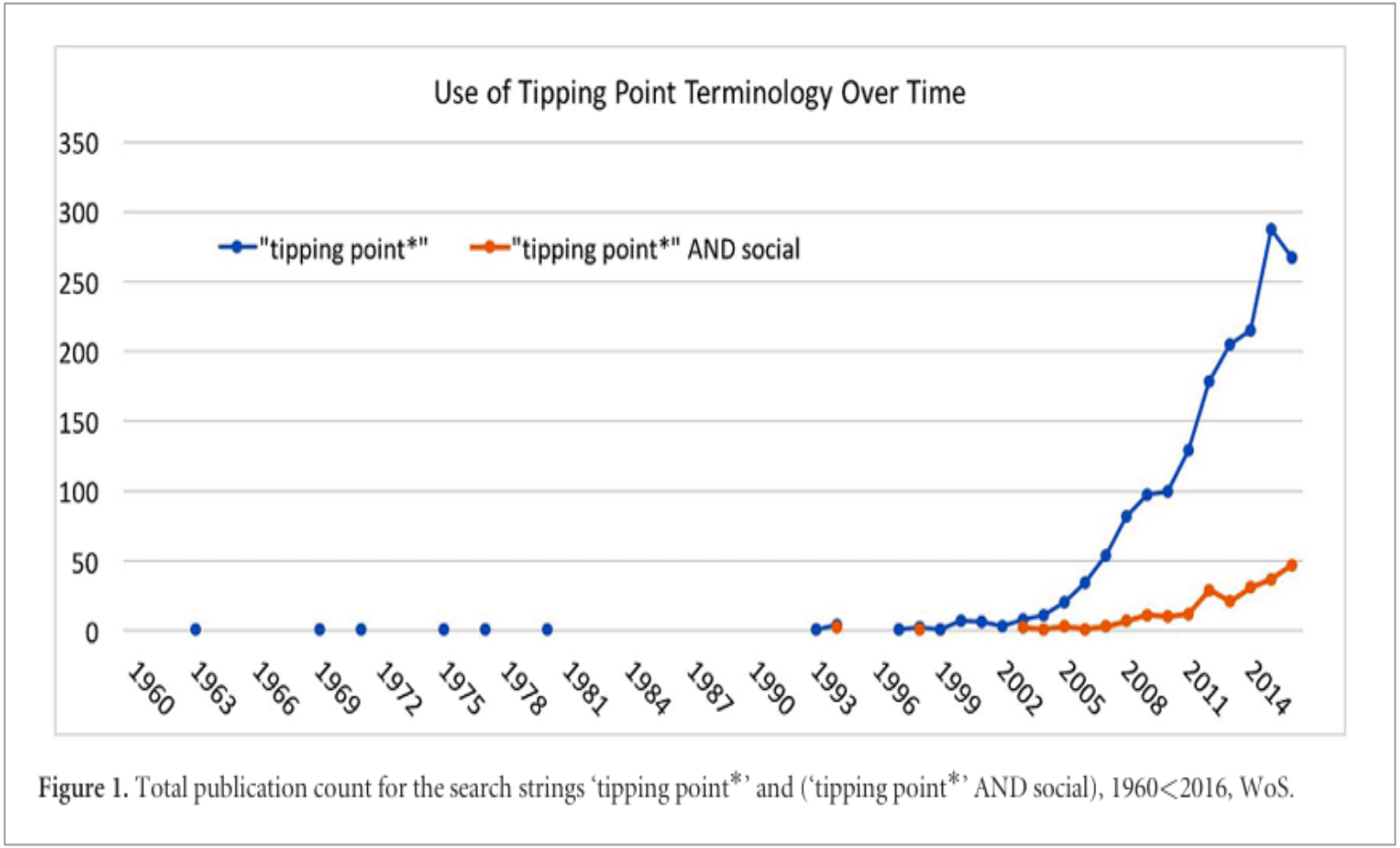


Figure 1. Total publication count for the search strings 'tipping point*' and ('tipping point*' AND social), 1960<2016, WoS.

Literature Review 1960-2016 (Milkoreit et al., 2018)

- "After a period of conceptual bandwagoning, the tipping point becomes the preferred term in scientific publications on non-linear change, superseding others. In our qualitative database, it is overall the most frequently used term (59% of papers), followed by threshold (44%), critical transition (30%) and regime shift (20%)."

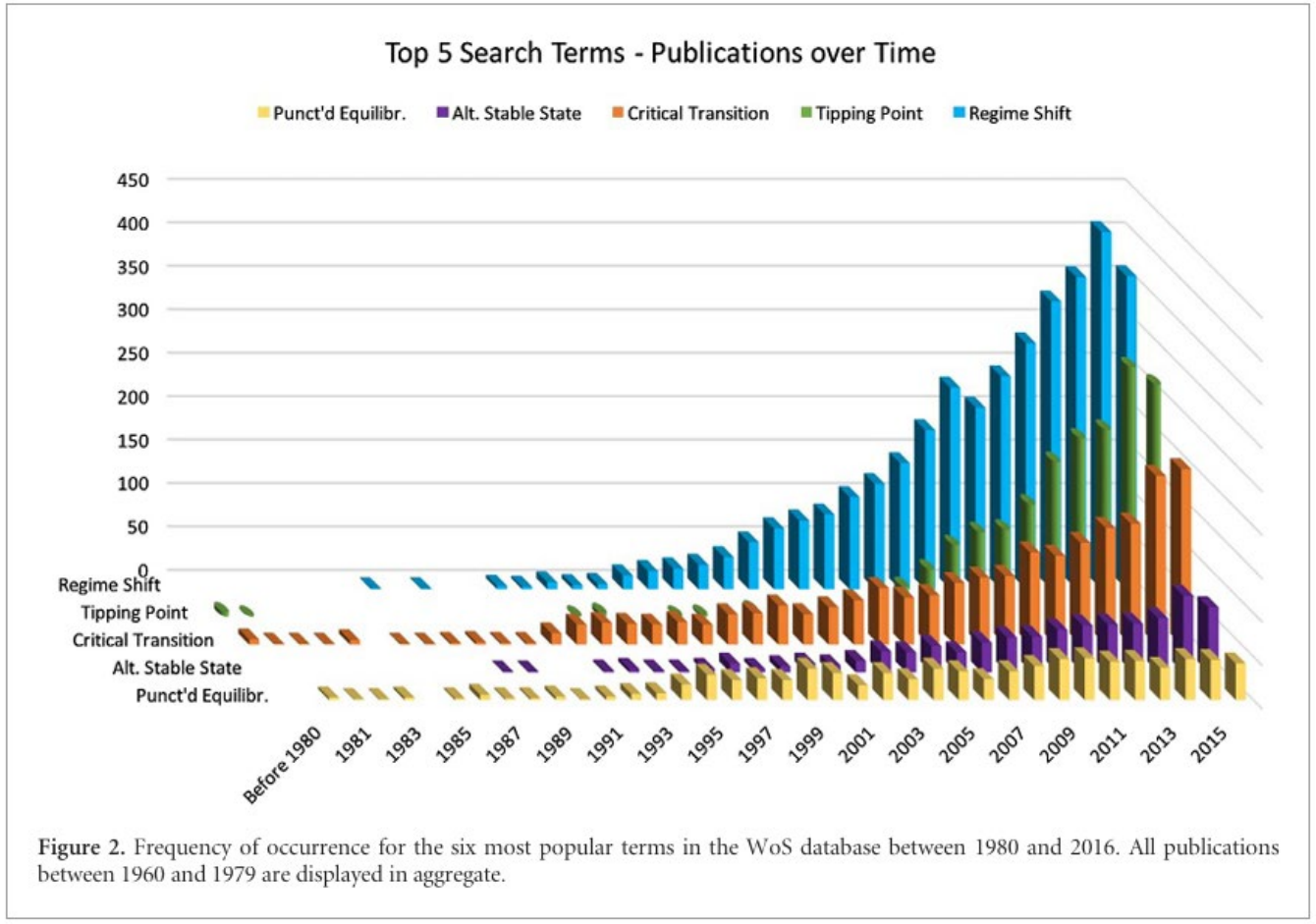


Figure 2. Frequency of occurrence for the six most popular terms in the WoS database between 1980 and 2016. All publications between 1960 and 1979 are displayed in aggregate.

Tipping points usually refer to a specific category of change processes with at least four characteristics:

(Milkoreit et al., 2018)
(Milkoreit, 2022)

- **Alternative stable states (equilibria):** system in question undergoes a fundamental restructuring from one stable state to another
- **Nonlinearity/abruptness:** Beyond a threshold (tipping point), the change process unfolds rapidly compared to a general background speed of the system. Nonlinearity is also referred to as disproportional causality—small causes can have large effects and vice versa
- **Positive feedback:** Self-amplifying feedback dynamics serve as main drivers of the change process (the mechanism generating nonlinear behavior)
- **(Limited) Irreversibility:** Reversibility has been a contested criterion of tipping dynamics. Many climatic tipping processes appear to be irreversible on human timescales. A range of systems exhibit hysteresis– the conditions for returning to the initial state differ from those that created the initial change. However, some climate tipping elements, such as the Arctic Summer Sea Ice, can return to their initial state if the driver of change is reversed. More generally, reaching a new "stable" state requires that the system remains in that state for a meaningful time span, not returning immediately to its pre-tipping state.

“overuse of the term tipping point to describe a variety of distinct phenomena” (Yletyinen et al. 2019)

- Regime change / shift
- Critical transition
- Transformation
- Technological change / disruption / adoption
- Phase change
- Ecosystem collapse
- State of the world change
- Perturbed equilibrium
- Threshold
- Failure
- Breakpoint
- Unintended consequences
- Cascading and compounding risks
- Disruptive change
- Planetary boundaries
- Positive feedbacks
- Nonlinear

“The term tipping point has become the most popular label for nonlinear state change processes across multiple disciplines over the last decade, surpassing older terms for the same phenomenon, including regime shifts and critical transitions” (Milkoreit, 2022)

Increasingly diverse conceptualizations of tipping points across multiple disciplines (Kopp et al., 2016)

“Is it [“tipping point”] intended as a scientific concept, or as a metaphor?” (Russill and Nyssa, 2009)

“Metaphorical use of a concept can mask important differences between two objects of study.” (Milkoreit et al., 2018)

Kopp et al. 2025 critique the ‘tipping point’ framing for oversimplifying the diverse dynamics of complex natural and human systems and for conveying urgency without fostering a meaningful basis for climate action.

Flash Talks

- Tipping Points and Planetary Boundaries (Etienne Berthet, CS3 Postdoctoral Associate)
- Tipping Points and Land Use (Angelo Gurgel, CS3 Principal Research Scientist)
- How the Science of Tipping Points Affects Decision-Making (Henry Jacoby, CS3 Faculty Affiliate and MIT Professor of Management Emeritus, MIT Sloan School of Management)

Tipping Points and Planetary Boundaries – Flash Talk

Etienne Berthet, CS3 Postdoctoral Associate

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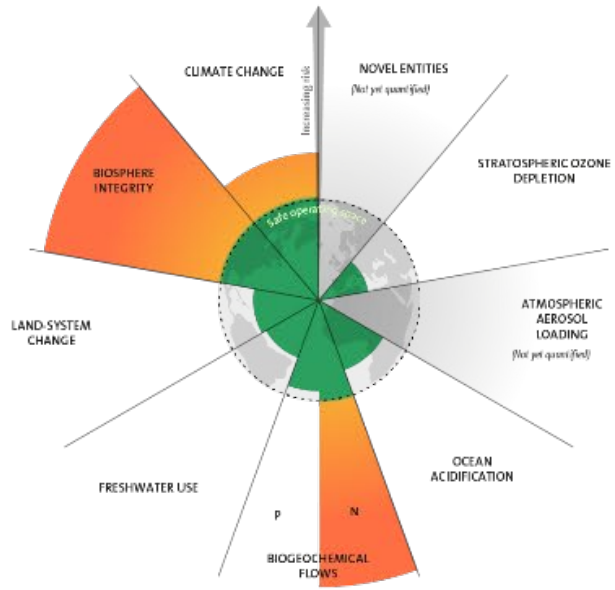
Planetary Boundaries – Defining a safe operating space for humanity

- **Planetary boundaries**: A scientific framework outlining Earth's **safe operating space**[1,2]. Identifying and delineating the **planetary limits within which humanity must operate to ensure its long-term survival** and development. Research in **Earth system science has unambiguously identified clear biophysical thresholds**, which outline the safe operating spaces for human activity[3,4].
- " *[…] biophysical and biochemical systems and processes known to regulate the state of the planet within ranges that are historically known and scientifically likely to maintain Earth system stability and life-support systems conducive to the human welfare and societal development experienced during the Holocene*" [3].
- Concept presenting a set of **nine planetary boundaries** within which humanity can continue to develop and thrive for generations to come.
- These nine boundaries have been scientifically scrutinized since their first introduction in 2009, suggesting that sustainable stewardship, **within scientifically defined boundaries**, gives humanity a good chance **of safeguarding the Earth system baseline in a Holocene-like state**, conducive to human development.

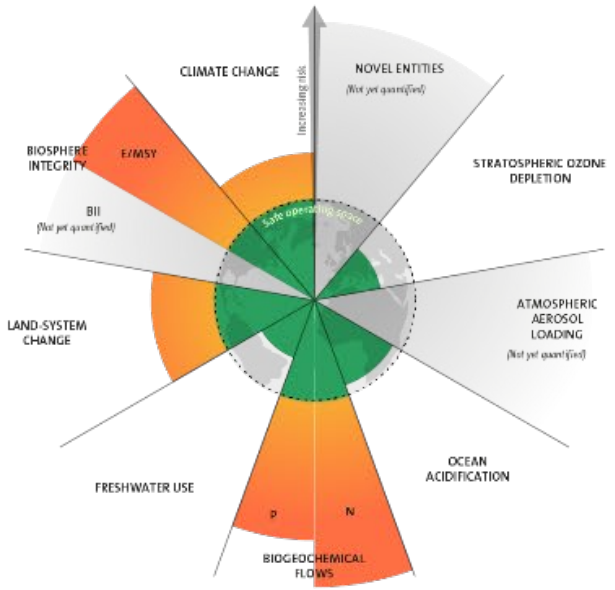
Planetary Boundaries – Defining a safe operating space for humanity

2009



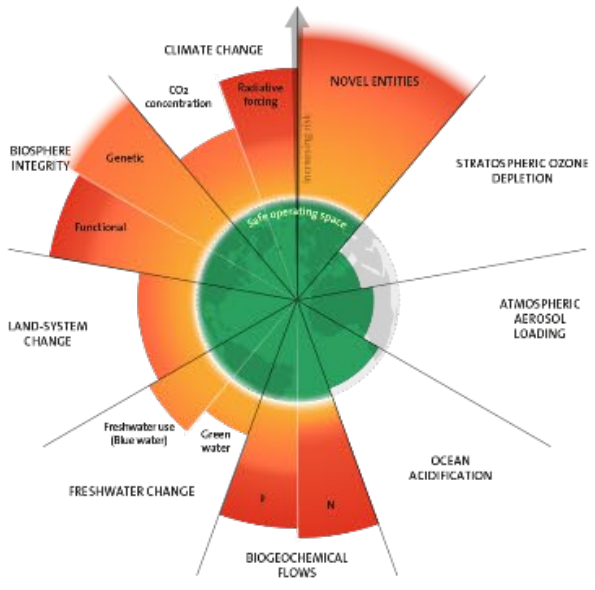
7 boundaries assessed,
3 crossed

2015



7 boundaries assessed,
4 crossed

2023



9 boundaries assessed,
6 crossed

Credit: Azote for Stockholm Resilience Centre, based on analysis in Richardson et al 2023.

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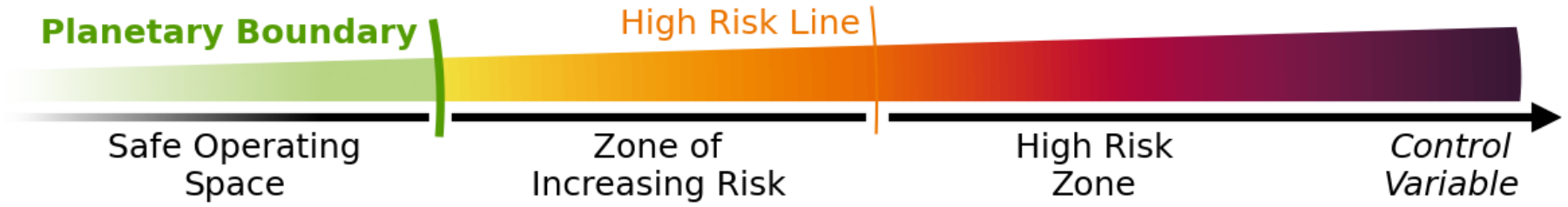
How are the Planetary Boundaries determined

- The changes encapsulated by the Planetary Boundaries arise from "*myriad human activities, ultimately aggregating to alteration of biomes*"[3]. As such, **control variables** are chosen to capture **the most important anthropogenic influence at the planetary level** of the boundary in focus.
- The planetary boundaries framework calls for a more deeply integrated modelling of the Earth's system by bringing together currently available evidence for the relevant processes and their interactions from different disciplines and sources.
- Control variables should ideally lend themselves to empirical determination and be computable for use in Earth system projections (e.g., process-based simulation of future change in forest cover) where possible.
- Boundaries = Control variable markers = Points at which various risks escalate beyond a safe level.



Source: https://www.pik-potsdam.de/en/output/infodesk/planetary-boundaries#faq-three
The current status of the nine Planetary Boundary systems and processes, data from the Planetary Health Check 2024.

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How are the Planetary Boundaries determined – control variables

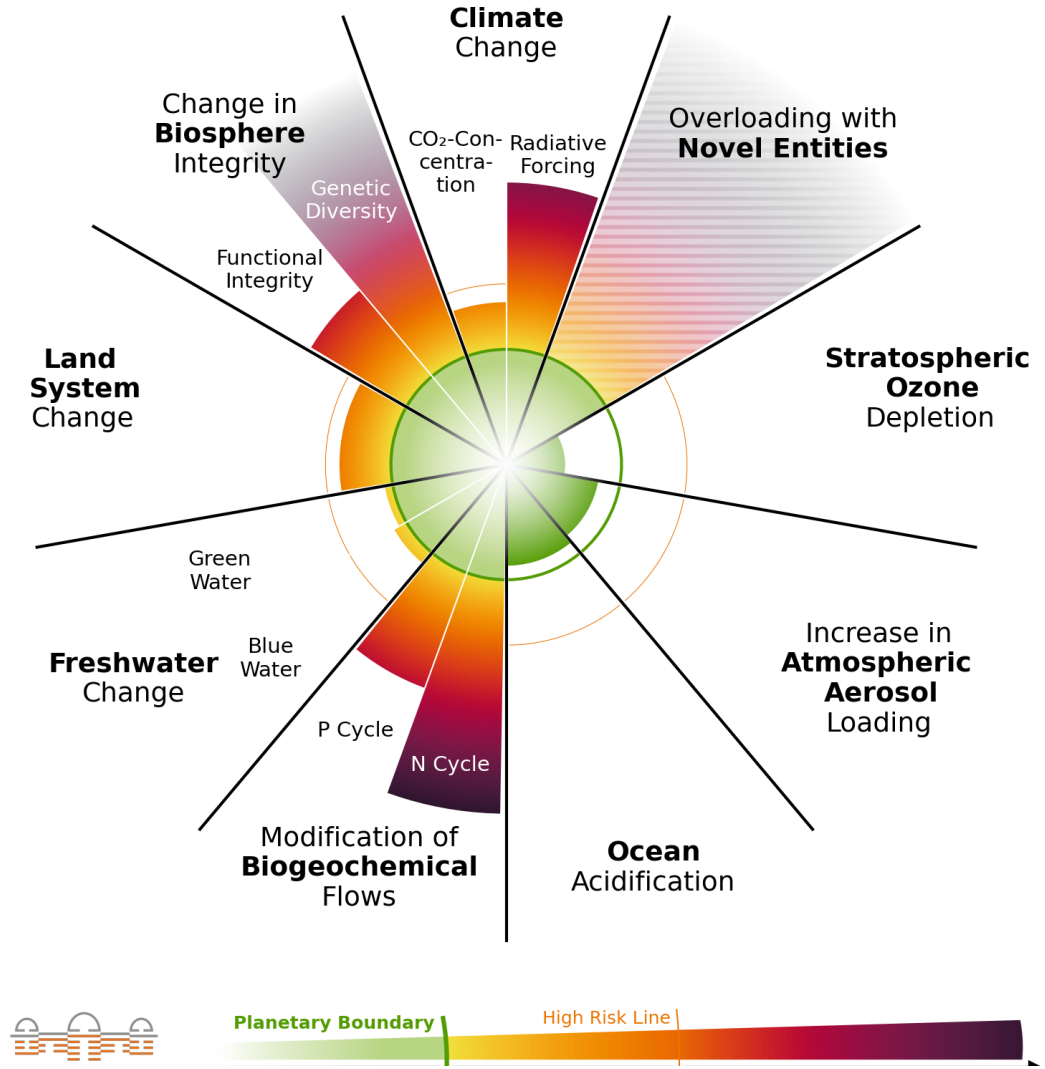
- ***"Despite data constraints, efforts have been made to identify suitable control variables for all boundaries"*** [3]. (Below Planetary boundary, 2023 value of control variable [3]).
- **Change in Biodiversity Integrity**
  - *Genetic Diversity*: measured in extinctions per million species-years (E/MSY): <10 E/MSY, >100 E/MSY
  - *Functional integrity*: Measured as energy available to ecosystems: photosynthetic energy and materials flow into the biosphere, i.e., net primary production (NPP), and define the boundary as a limit to the human appropriation of the biosphere's NPP (HANPP). Measured in billion tons of C $year^{-1}$ and expressed in % of HANPP compared to NPP: <10%, 30%
- **Climate Change**
  - Atmospheric CO_2 concentration (ppm CO_2): 350 ppm CO_2 , 417 ppm CO_2
  - Total anthropogenic radiative forcing at top-of-atmosphere (W m^{-2}): 1 W m^{-2}, 2.91 W m^{-2}
- **Stratospheric ozone depletion**
  - Stratospheric O_3 concentration, (global average by latitude) Measured in Dobson units (DU**):** 276 DU**,** 284.6 DU
- **Freshwater change**
  - Percentage of annual global ice-free land area with streamflow/root-zone soil moisture deviations from preindustrial variability. Determined at the 30 arc-min grid cell scale and further aggregated to a global annual value. For both blue and green water control variables, boundaries are set at the 95th percentile of preindustrial variability.
    - Blue Water: 10.2% 18.2%
    - Green Water: 11.1%, 15.8%

How are the Planetary Boundaries determined – control variables

- **Ocean acidification**
  - The carbonate ion concentration, average global surface ocean saturation state with respect to aragonite (Ω_{arag}): 2.75 Ω_{arag}, 2.8 Ω_{arag}
- **Biogeochemical flows: P and N cycles**
  - *Phosphate global*: flows from freshwater systems into the ocean (Tg of P year^{-1}): 11 Tg of P year^{-1}, 22.6 Tg of P year^{-1}
  - *Phosphate regional:* flows from fertilizers to erodible soils (Tg of P year^{-1}): 6.2 Tg of P year^{-1}, 17.5 Tg of P year^{-1}
  - *Nitrogen global*: industrial and intentional fixation of N (Tg of N year^{-1}): 62 Tg of N year^{-1}, 190 Tg of N year^{-1}
- **Land system change**
  - *Global*: area of forested land as the percentage of original forest cover 75%, 54%;
  - *Biome*: area of forested land as the percentage of potential forest (% area remaining);
    - Temperate 50%, 30%,
    - Tropical 85% 60%,
    - Boreal 85%, 60%
- **Novel entities**
  - Percentage of synthetic chemicals released to the environment without adequate safety testing: 0%, transgressed

What happens if we transgress a boundary?

- **Crossing the Threshold**
  - Once boundaries are transgressed, the system enters a “zone of uncertainty” (danger zone)[5].
  - Risks rise, but scientific evidence remains scattered.
- **Entering High-Risk Zone**
  - As uncertainty narrows, we reach the high-risk zone with stronger evidence of potential damage.
- **Long-Term Implications**
  - No immediate catastrophe, but continued transgression elevates the long-term risk of destabilizing Earth’s life-support systems.



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Example of misrepresentation of the Planetary Boundaries framework: biodiversity boundary

Trends in Ecology & Evolution

CellPress
REVIEWS

Forum

Planetary Boundaries for Biodiversity: Implausible Science, Pernicious Policies

José M. Montoya,[1,*]
Ian Donohue,[2] and
Stuart L. Pimm[3]

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.

How Should We Manage Human Actions That Harm Biodiversity?

Human actions obviously harm the natural world and, as we reduce the populations of species and drive some to extinction, we change ecosystems. How best should environmental science articulate its concerns, set research agendas, and advise policies? One solution embraces the notion of planetary boundaries [1]. Despite widespread criticisms, the tipping-point claim persists, with recent reproduction of the original claim [1] and statements[ii] that the threshold is 'not arbitrary', emerges from 'massive amounts of data' from many fields, and that 'no one is saying that the idea is wrong', despite 'massive breakthroughs in counting extinctions'. As we explain in Box 1, none of these statements are justified.

Drawing attention to global environmental issues is certainly essential, therefore what harm is there in another approach, superficially attractive even if it has limitations? We argue that notions of planetary boundaries add no insight into our understanding of the threats to biodiversity and ecosystem functioning, have no evidence to support them, are too vague for use by those who manage biodiversity, and promote pernicious policies. Attempts to fix these problems strip the original idea of all meaningful content, but still plead for the notion of a safe operating space. Why is this deeply flawed idea so seductive, and what problems arise from its embrace?

To address concerns that extinction rates are an inappropriate metric, the biodiversity boundary is renamed as 'biosphere integrity' [3]. Two static measures of biodiversity replace rates: phylogenetic variability and functional diversity. Problems of definition apart, reliable estimates for anything resembling these are impossible to obtain at regional to global scales.

Confronted with the inappropriateness of their measures, we are urged to keep using 'in the interim' extinction rates – already shown to be flawed – and a 'biodiversity intactness index' [3]. The latter is the average abundance of a broad range of species relative to their abundance in an undisturbed habitat. The boundary is set at >90%, assessed geographically across biomes or other large areas. This proliferation of indices adds no useful insight. Even if we were able to estimate the necessary numbers, their limits are arbitrary.

Finally, the purported threshold occurs for the response variable of 'biosphere functioning'. Neither theory nor empirical data support any threshold of biodiversity below which ecosystem function is

Box 1. Why Tipping Points for Biodiversity Are Fatally Flawed

Conflating tipping points with planetary boundaries

Clarification:

- **No Single Global Biodiversity Tipping Point**: The Planetary Boundaries research does not assert a planetary-scale biodiversity tipping point.
- **Not a Replacement**: It is not intended to replace ecosystem management approaches, but to complement them with Earth system perspectives.

Complementarity:

- **Works Alongside Other Approaches:** The framework **complements existing conservation policies**, such as payment schemes for ecosystem services, marine protected areas, and Aichi targets.
- **Integrating Global and Local Efforts:** Rather than substituting ecosystem management, it broadens the scope by integrating Earth system considerations into sustainability initiatives.

Conclusion: Are planetary boundaries the same things as tipping points?

- Short: **No**
- Long:
  - "**Tipping points** are **thresholds** beyond which certain critical, large-scale components of the Earth system can be tipped into a qualitatively new state, often characterized by far-reaching changes to conditions on Earth" [5].
  - **"Planetary Boundaries**, on the other hand, **are demarcations for where various risks rise above a safe level**. Such a risk may rise in a s**mooth and gradual way, without any thresholds**" [5].
    - *Remark:* In some cases, a Planetary Boundary is set specifically to prevent crossing known tipping thresholds. For example, the climate change boundary was chosen to keep global warming below critical tipping elements.

- **Transgression ≠ Tipping Point.** Exceeding a Planetary Boundary does not necessarily mean a tipping point has been crossed. However, tipping point science is one of the key data sources used to define these boundaries—ensuring Earth system thresholds remain intact.

Source: https://www.pik-potsdam.de/en/output/infodesk/planetary-boundaries

Tipping Points and Land Use

Angelo Gurgel

Some slides were prepared based on a CS3 study co-authored by John Reilly and Elodie Blanc

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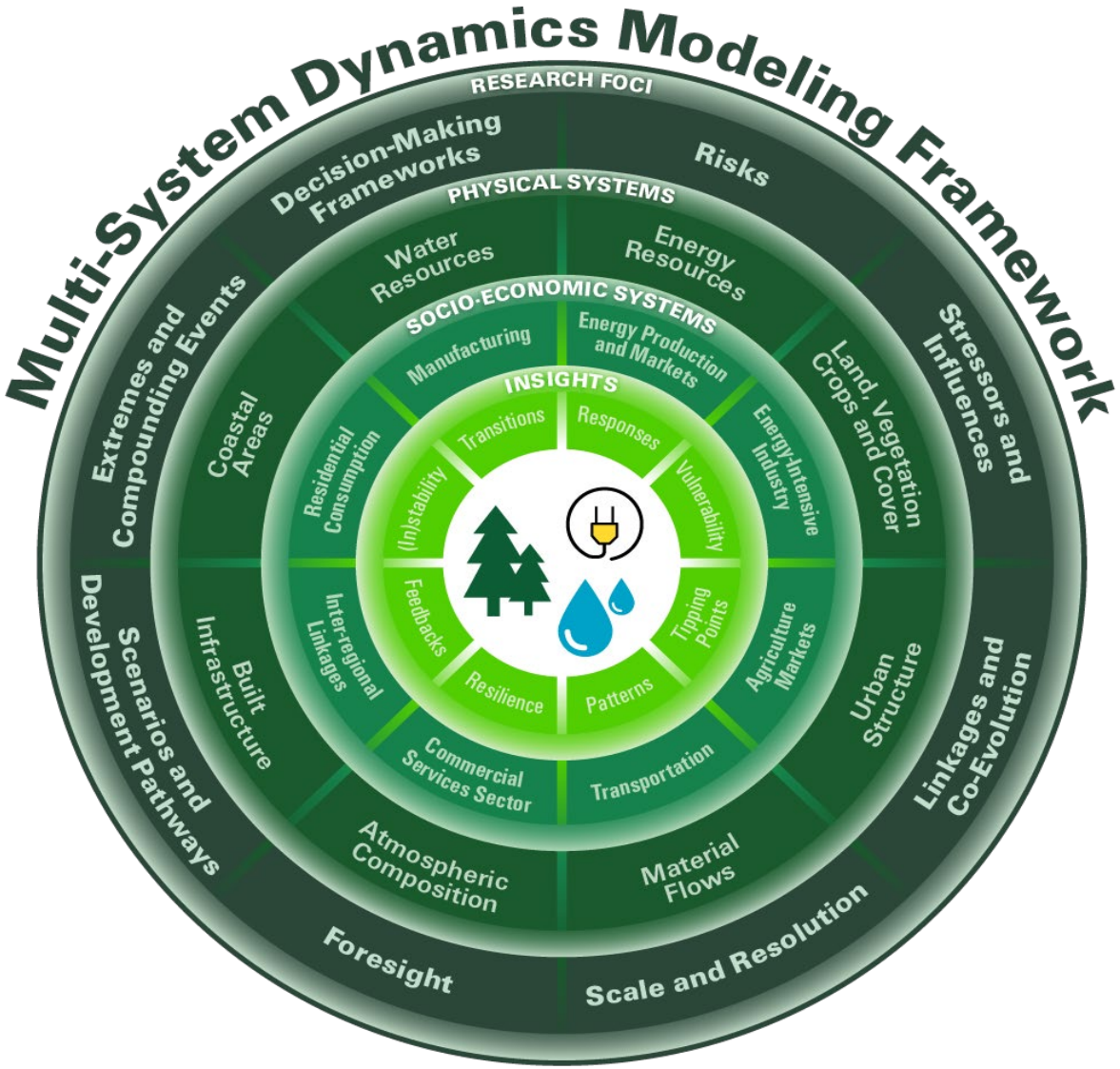
U.S. DEPARTMENT OF ENERGY | Office of Science
BIOLOGICAL AND ENVIRONMENTAL RESEARCH
Earth and Environmental System Modeling

Summary

- Investigating tipping points applied to land use changes in the US:
  - *Framework*
  - *Our research question/goal*
  - *How to define/contextualize/measure tipping points*
  - *Illustrative results*

Framework

- ***Multisectoral, multisystem dynamics (MSD)*** perspective focused on understanding dynamics in complex interdependent systems;
- ***Interactions among human systems and natural systems***;
- Allows investigating ***vulnerability or resilience of systems to compounding forces and stressors***;
- Develop and combine different ***tools/capabilities to analyze multiple system dynamics simultaneously*** and how they may compound to “break the system” or cause ***tipping points***.



Research Question

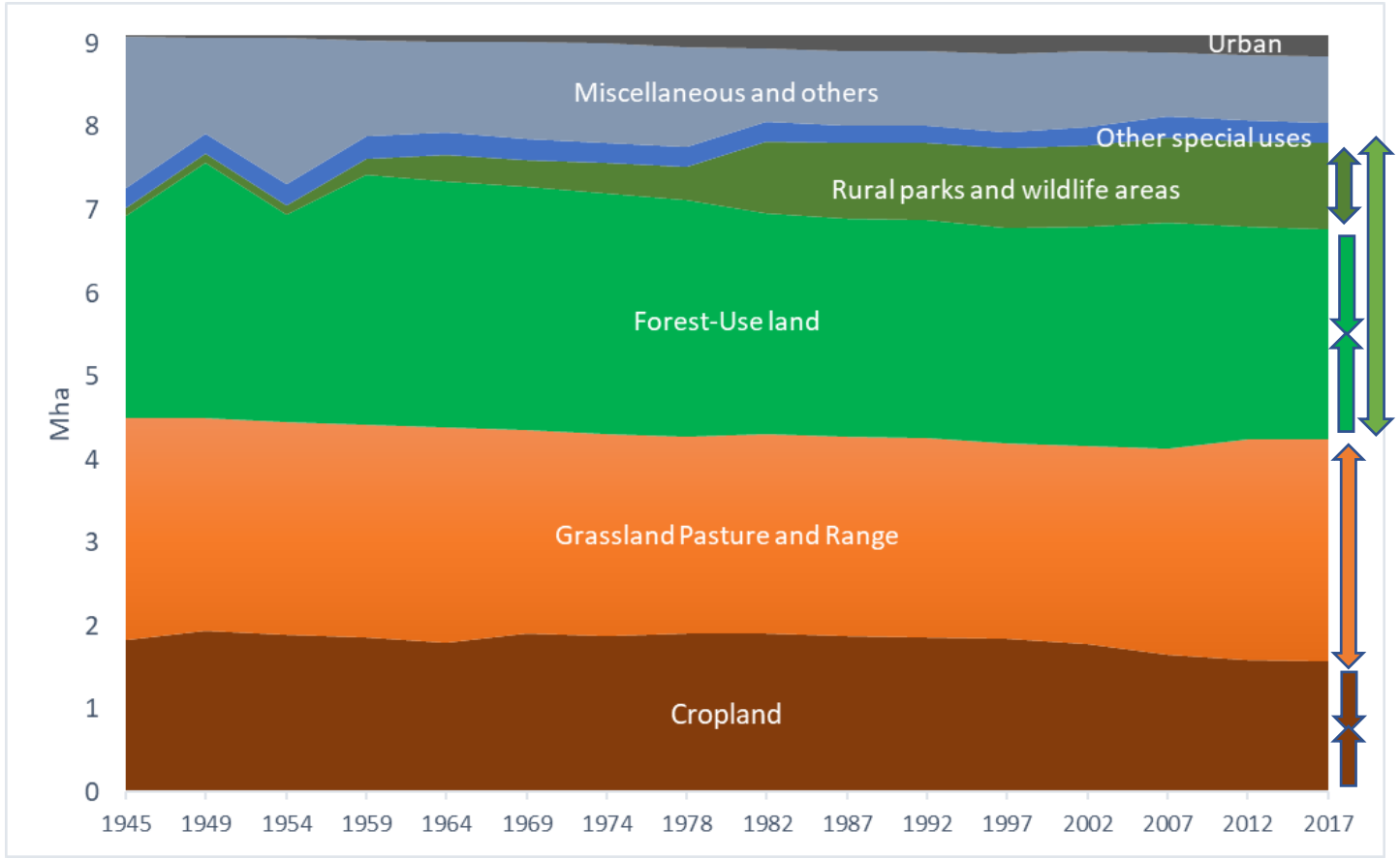
- How global forces could affect land use in the US and the potential for tipping points?

Agriculture land in the U.S. has been fairly stable in the last 50-60 years

Multiple forces influencing land use changes at the global level:

- *income and population growth*
- *yield and productivity improvements*
- *trade policy*
- *climate change*
- *changing diets*

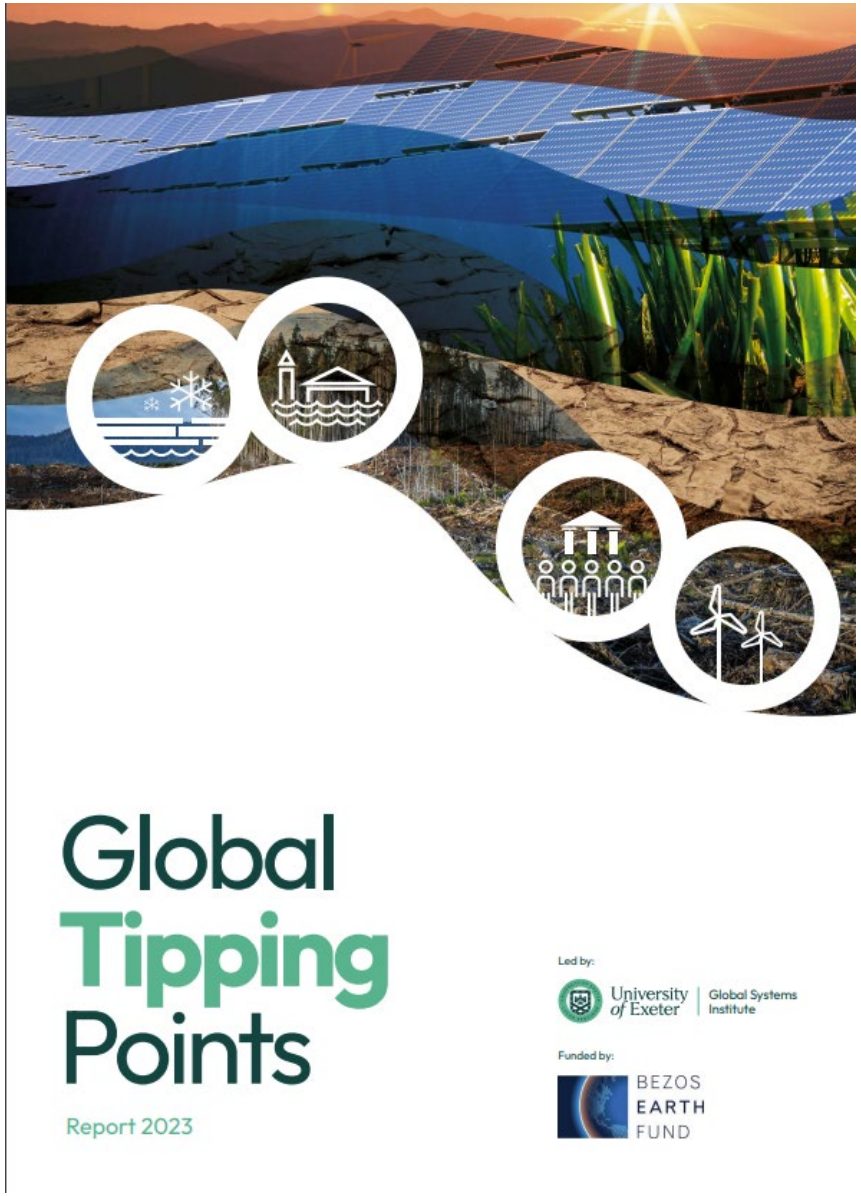
Major Uses of Land in the United States



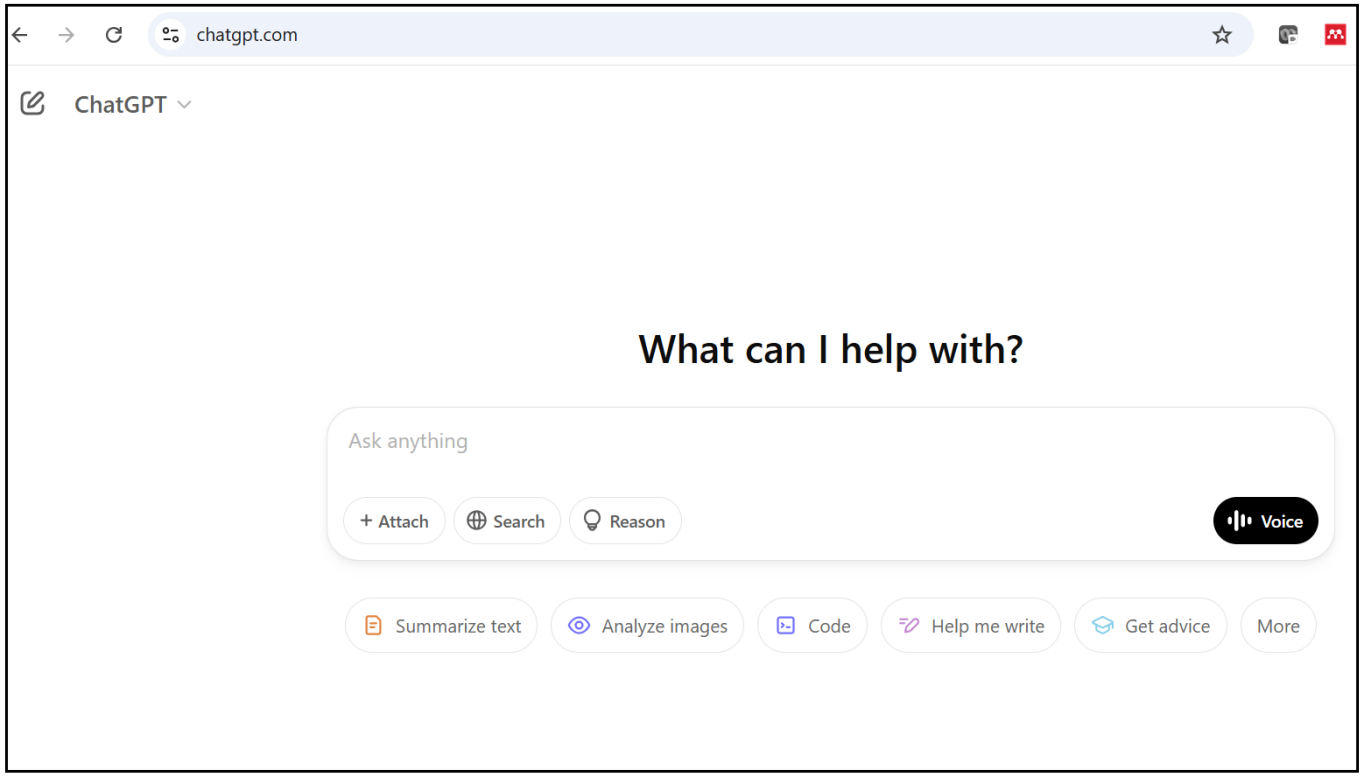
* *Other special uses* includes “farmsteads, roads, and miscellaneous farmland”, “land in defense and industrial areas” and “land in rural transportation facilities”

Source: Winters-Michaud, 2024

Tipping Points



ChatGPT



Lenton et al. 2023

Tipping Points

Global Tippint Points Report
(Lenton et al., 2023)

- Where a **small change** makes a big difference to a system (Gladwell, 2000), or
- "the point at which a series of **small changes** or incidents becomes significant enough to cause a larger, more important change" (Oxford English Dictionary).
- It is a type of **threshold**.
- The small change that causes a system to pass a tipping point can be described as a **trigger**.
- The resulting large change can be described as a **qualitative change** in what a system looks like or how it functions
- The change commonly includes qualities of (Milkoreit et al., 2018):
  - **abruptness** (change is rapid relative to its drivers);
  - **self-perpetuation** (will continue even if the forcing is removed, until a new state is reached);
  - **irreversibility** (change is difficult or impossible to reverse).
- It includes the possibilities of ***non-abrupt*** and ***reversible*** tipping points.

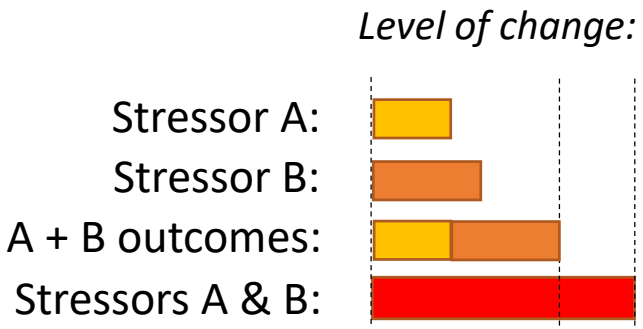
ChatGPT

Refer to critical **thresholds** in a system where a **small change** can lead to a significant and often **irreversible** shift in the system's state. The concept is used in various fields, including:

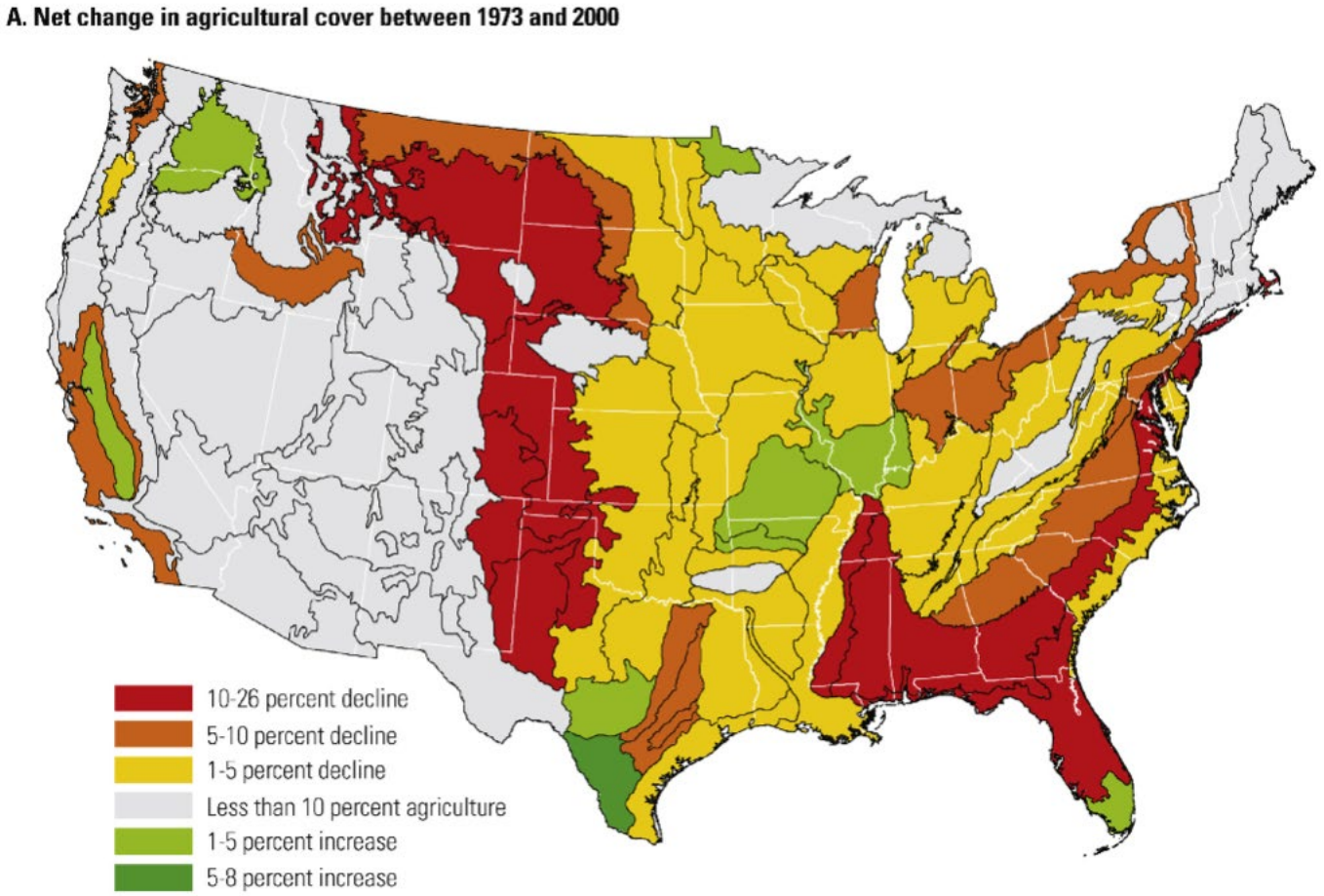
1. ***Climate Science*** – A tipping point in the climate system occurs when a small increase in global temperature triggers large, self-reinforcing changes (e.g., ice sheet collapse, Amazon rainforest dieback).
2. ***Sociology*** – In social movements, a tipping point is the moment when a minority view or behavior spreads rapidly and becomes mainstream.
3. ***Economics*** – In markets, a tipping point can refer to when a small change (such as new technology or policy) leads to widespread adoption or collapse.
4. ***Epidemiology*** – In disease spread, a tipping point marks when an outbreak moves from a manageable situation to an uncontrollable epidemic.

Tipping Points

Multiple and compounding forces: is there a tipping point in land use in the US?



"Land-cover change in the conterminous United States from1973 to 2000"

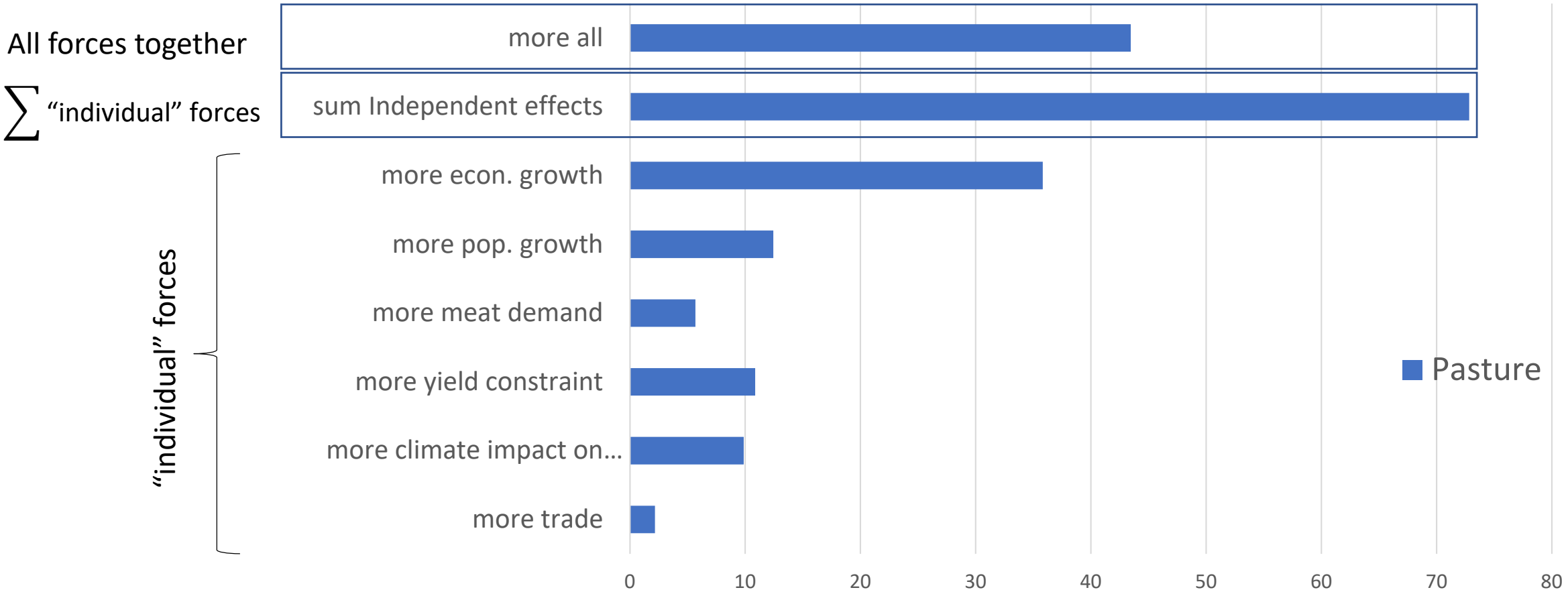


Source: Sleeter et al. (2013)

Illustrative Results

Land use changes in 2050 relative to BAU in US (Mha)

(scenarios with higher pressures toward agricultural land expansion)



Source: Gurgel et al. (2021)

Final remarks

- Tipping points definition and scope and how it relates to:
  - ✓ research question
  - ✓ science field and interdisciplinarity of the research
  - ✓ Reversibility x irreversibility
  - ✓ Abrupt x gradual

- Methods to investigate tipping points in socio-economic models and interdisciplinary research:
  - ✓ Optimization models
  - ✓ Market equilibrium and price responses

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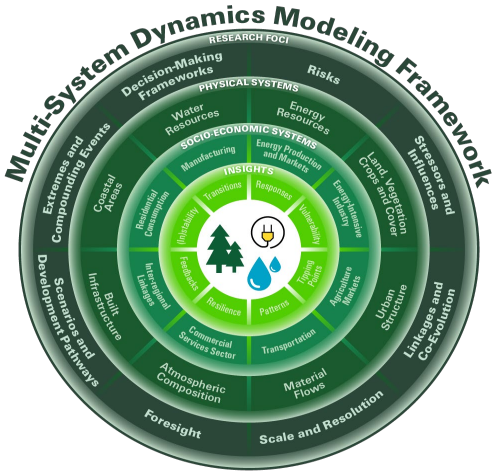

Thanks for your attention!

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How the Science of Tipping Points Affects Decision-Making

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(Verbal Comments, No Slides)

Breakout Discussions

- Discussion Questions:
  - Q1: What are examples of “tipping points” in (and between) physical and social systems?
  - Q2: Is the “tipping point” concept relevant for organizing research?
  - Q3: How might research address tipping points (or alternative concepts)?
  - Q4: What topics would you like to see explored in follow-up workshops?

- For each Breakout Group:
  - Shared Google Doc
  - Put your thoughts down - even if you speak them!

- Please engage in lively discussion - thank you!

Center for Sustainability Science and Strategy

Thank You!

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References: Planetary Boundaries Talk

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