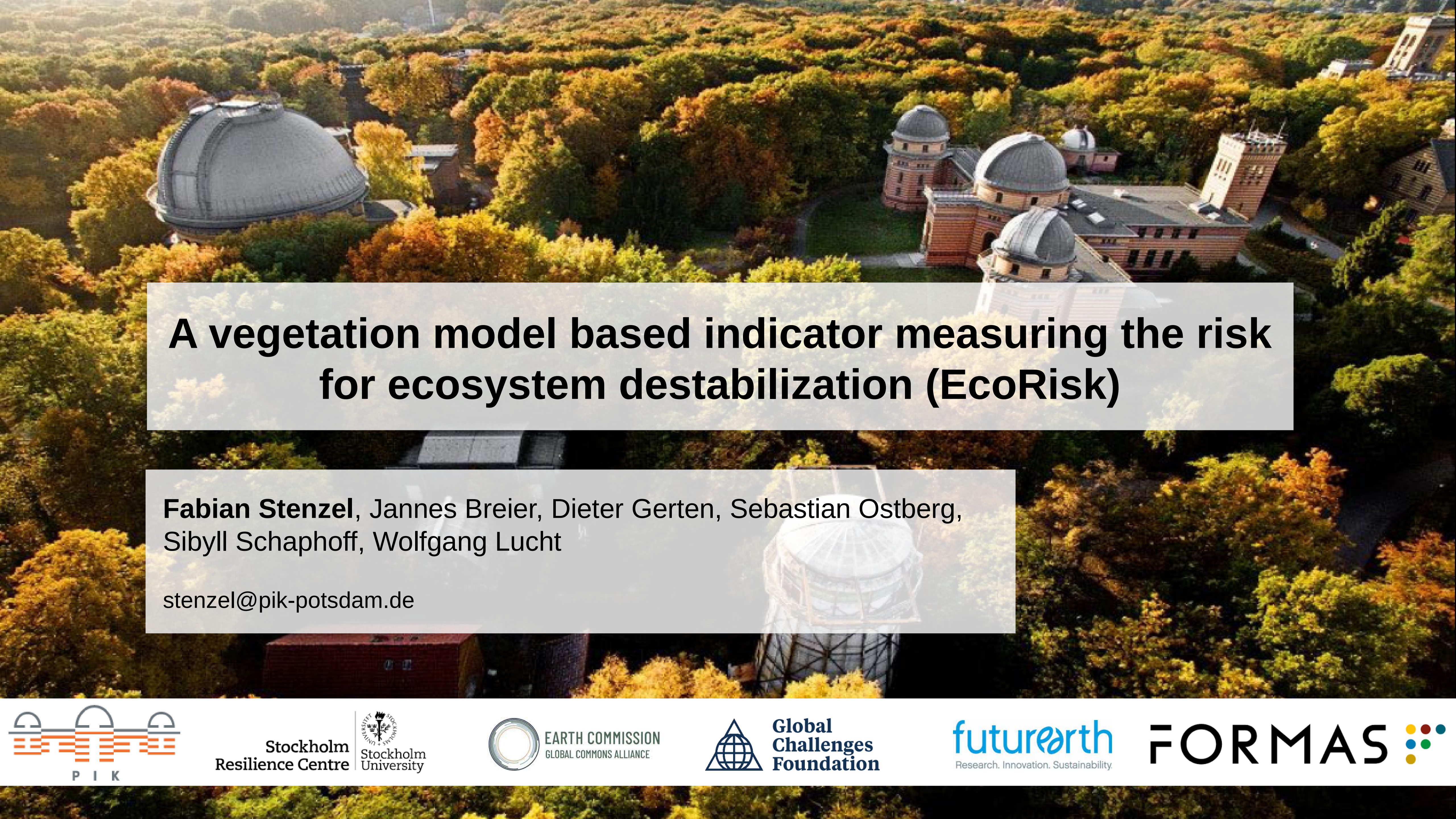

A vegetation model based indicator measuring the risk for ecosystem destabilization (EcoRisk)

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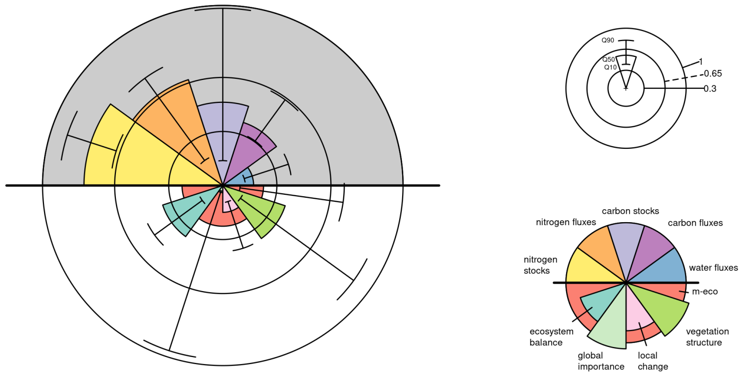
biospheremetrics R package

EcoRisk

Risk of ecosystem destabilization

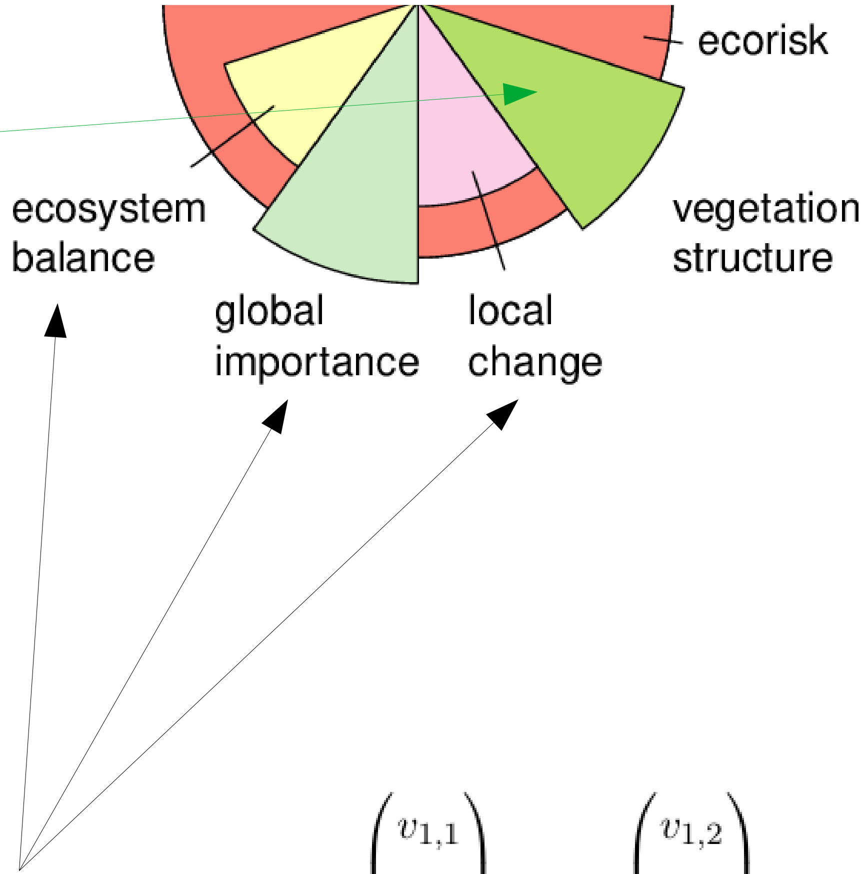
- Multidimensional ecosystem state metric
- Measuring shifts in biogeochemistry (water, carbon, nitrogen, vegetation)
- Consequences of ecosystem pressure (land use, extraction + climate change)
- proxy for the systemic risk of biosphere destabilization

Stenzel et al. 2024 (GMD)
https://github.com/stenzelf/biospheremetrics



Variables required for computing EcoRisk

Process description
grid data
plant surface cover
vegetation nitrogen pool
soil nitrogen pool
nitrogen outflow
nitrogen inflow
vegetation carbon pool
soil carbon pool
carbon inflow
carbon outflow
soil water pool
water inflow
water outflow
other



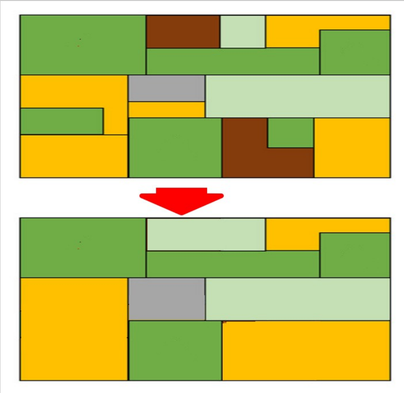
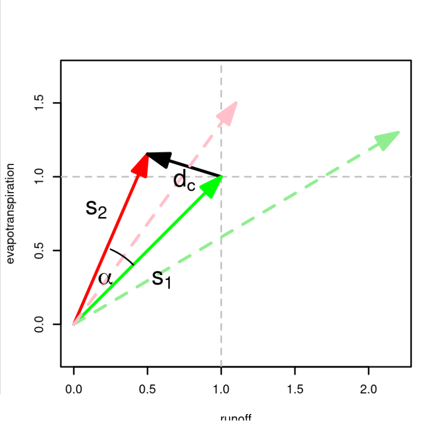
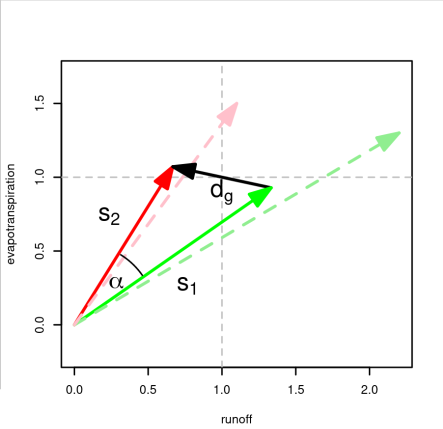
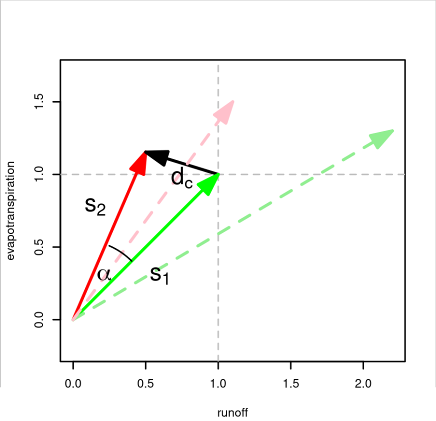
state vectors

$$\vec{s_1} = \begin{pmatrix} v_{1,1} \\ \vdots \\ v_{n,1} \end{pmatrix}, \vec{s_2} = \begin{pmatrix} v_{1,2} \\ \vdots \\ v_{n,2} \end{pmatrix},$$

Based on previous work by Sykes et al. 1999, Heyder et al. 2011, Ostberg et al. 2013/2015/2018

Differences between the EcoRisk components

$$\text{EcoRisk} = \frac{vs + lc + gi + eb}{4} = \frac{V \cdot S(V, \sigma_V) + l \cdot S(l, \sigma_l) + g \cdot S(g, \sigma_g) + e \cdot S(e, \sigma_e)}{4}$$

vegetation structure	local change	global importance	ecosystem balance
• dissimilarity of the vegetation composition	• changes compared to the **local reference state**	• local changes **in perspective to the global mean reference** condition	• **shifts** in the relative magnitude of biogeochemical properties with respect to each other
	• normalized with the **local values** of the reference state	• normalized with the **global**, spatially averaged reference **mean value**	• **angle** between the two state vectors with local normalization
			

Change-to-variability-ratio: $S(x, \sigma_x) = \frac{1}{1 + e^{-4\left(\frac{x}{\sigma_x} - 2\right)}}$

LPJmL model overview

LPJmL pjmlkit biospheremetrics LPJmL pycoupler LPJmL

- Process-based dynamic global vegetation model
- inputs: climate, soil, land use, management
- including agriculture
- full carbon, water and nitrogen cycles
- provides state variables and fluxes

Carbon

GPP	gross primary production
Ra	autotrophic respiration
Rh	heterotrophic respiration
Ch	harvested carbon
Cf	fire carbon fluxes
Csom	soil organic matter C

Water

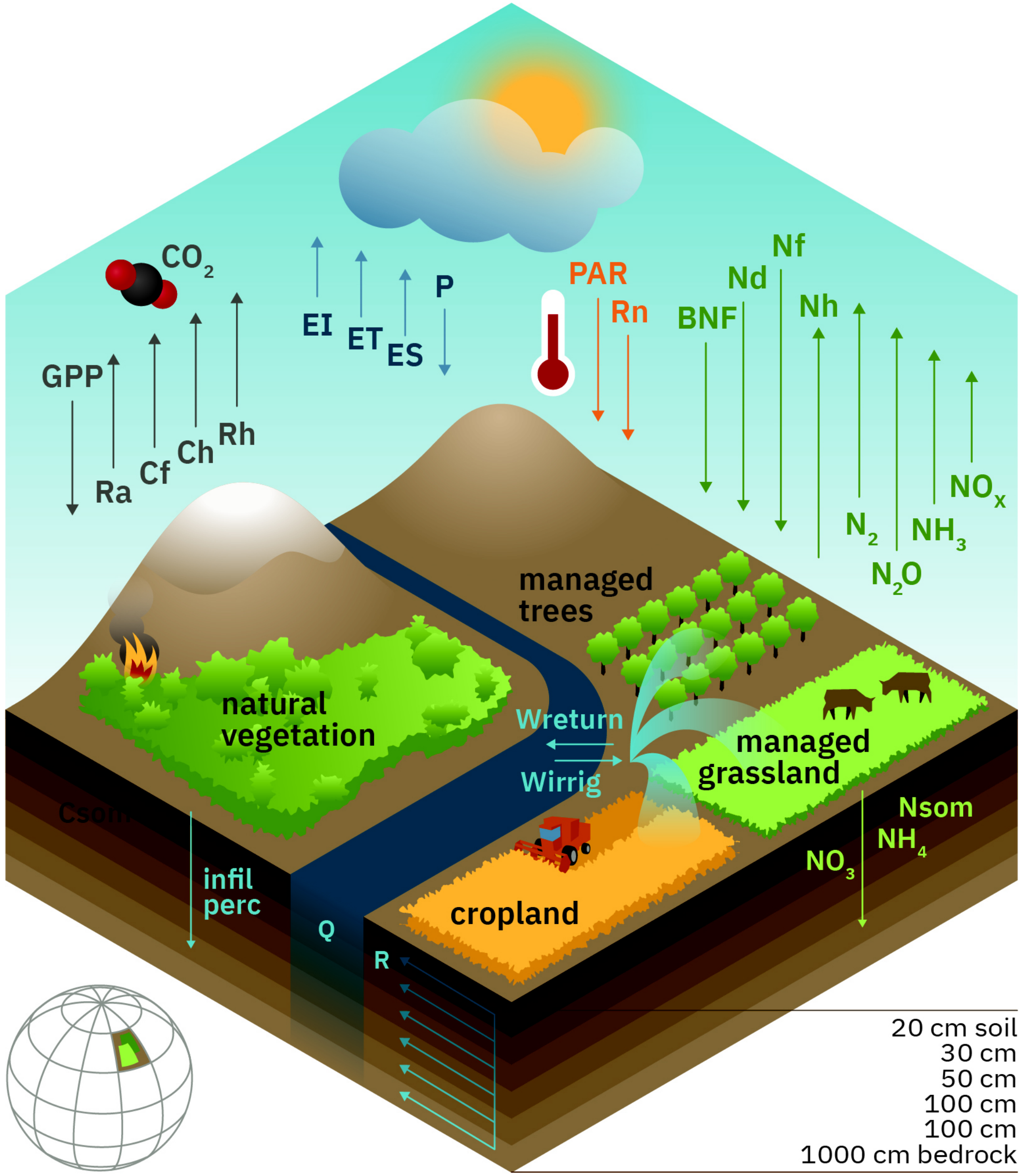
EI	interception
ET	transpiration
ES	evaporation
P	precipitation
perc	percolation
infil	infiltration
R	runoff
Wreturn	return flow of irrigation
Wirrig	irrigation water
Q	discharge

Energy

PAR	photosynthetic active radiation
Rn	net radiation

Nitrogen

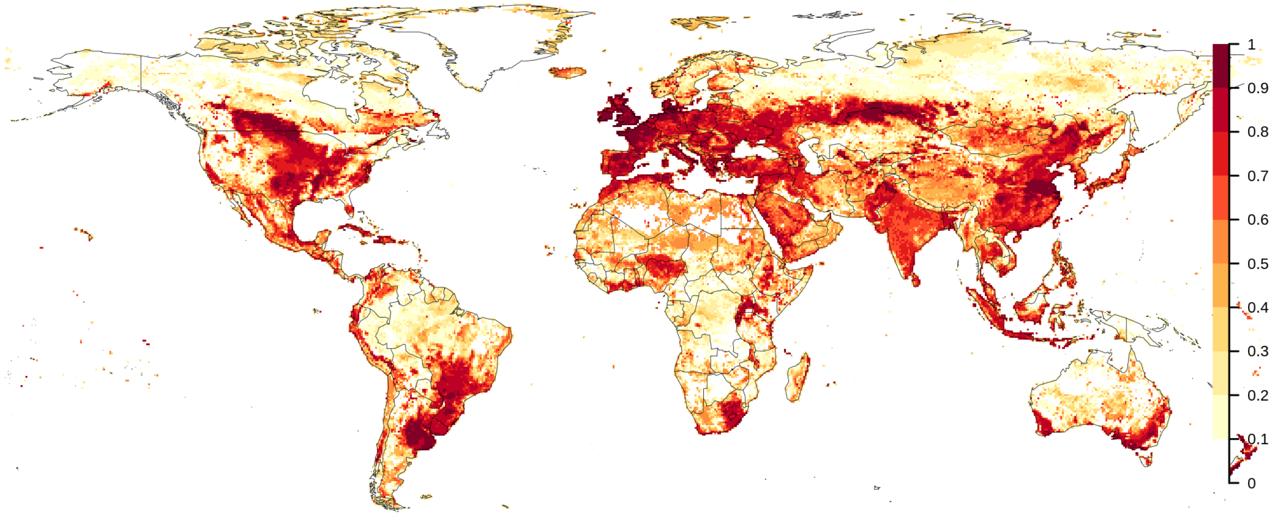
BNF	biological N fixation
Nf	fertilizer/manure input
Nd	atmospheric deposition
Nh	harvested nitrogen
N_2	molecular N emission
N_2O	nitrous oxide emissions
NH_3	ammonia volatilization
NO_x	nitrogen oxides emissions
Nsom	soil organic matter N



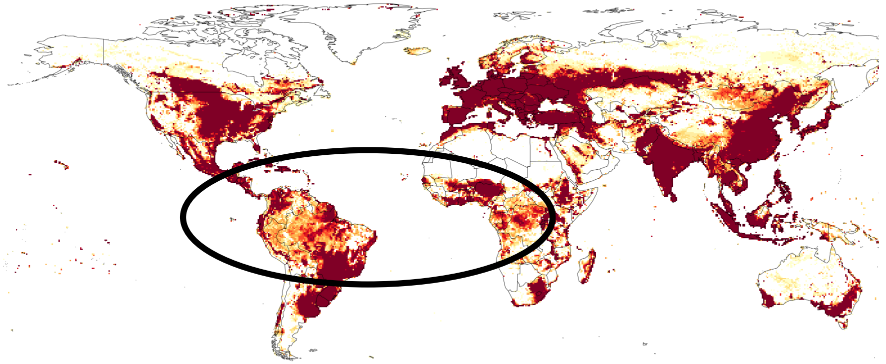
Schaphoff et al. 2018a/b, von Bloh et al. 2018, … , Heinke et al. 2023, Wirth et al. 2024

EcoRisk (component) maps highlight degradation risks

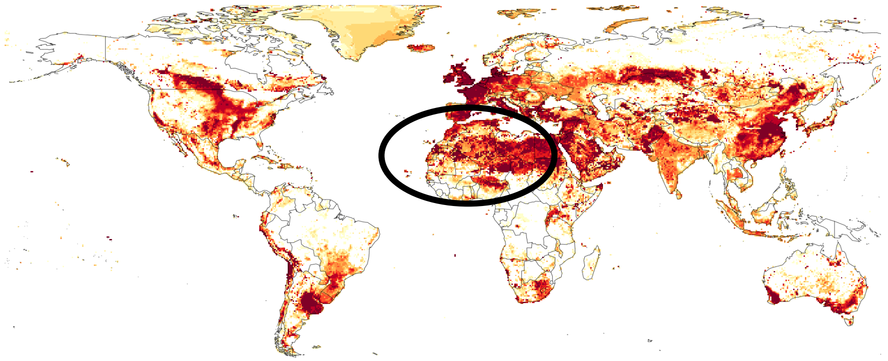
total EcoRisk (1987-2016 wrt 1550-1579)



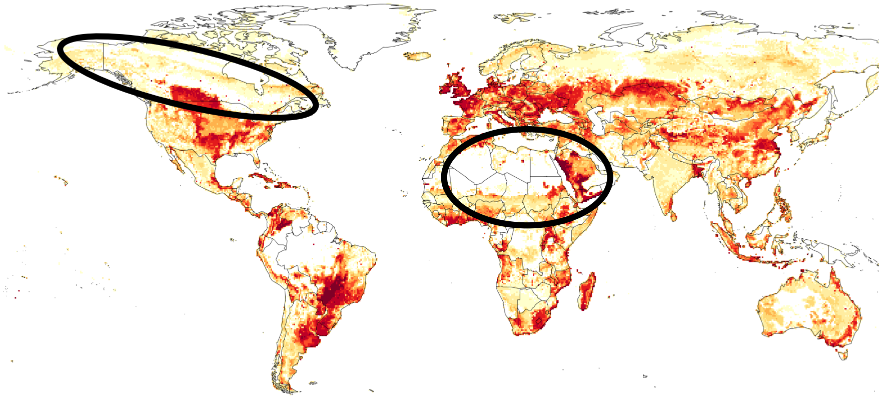
global importance



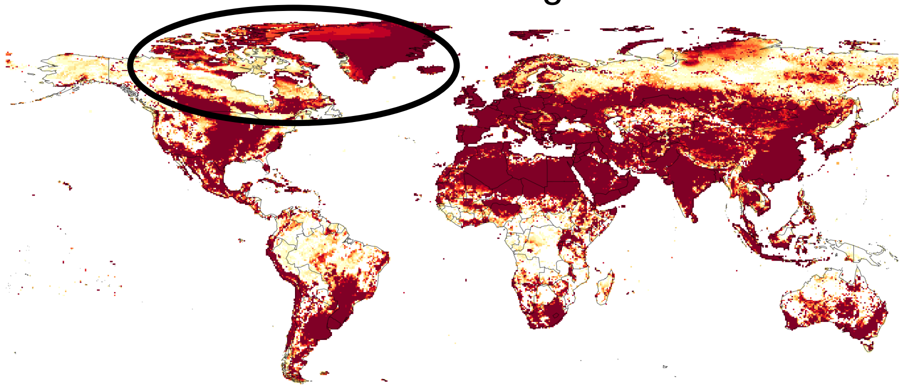
ecosystem balance



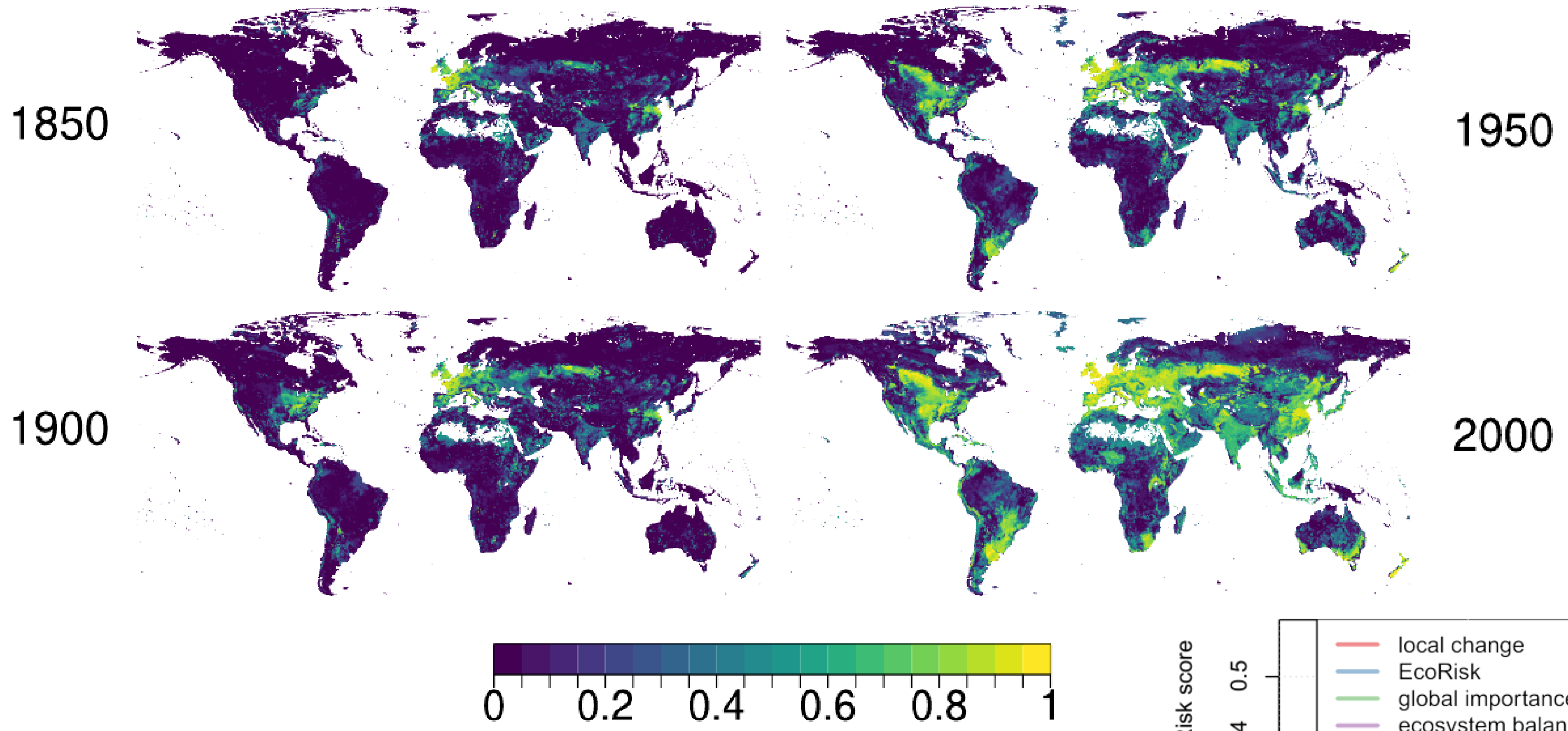
vegetation structure

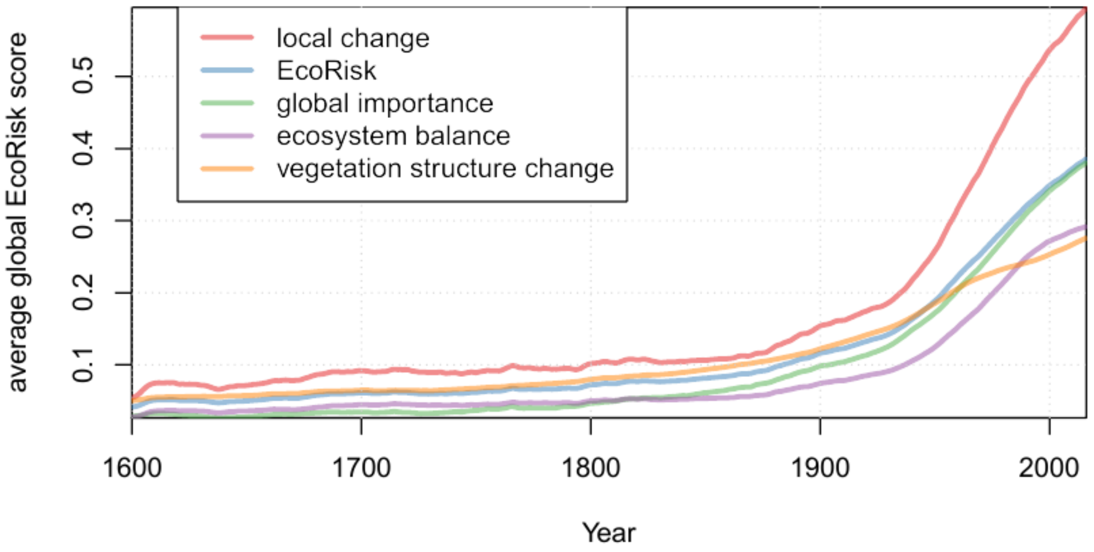


local change



Mapping through time



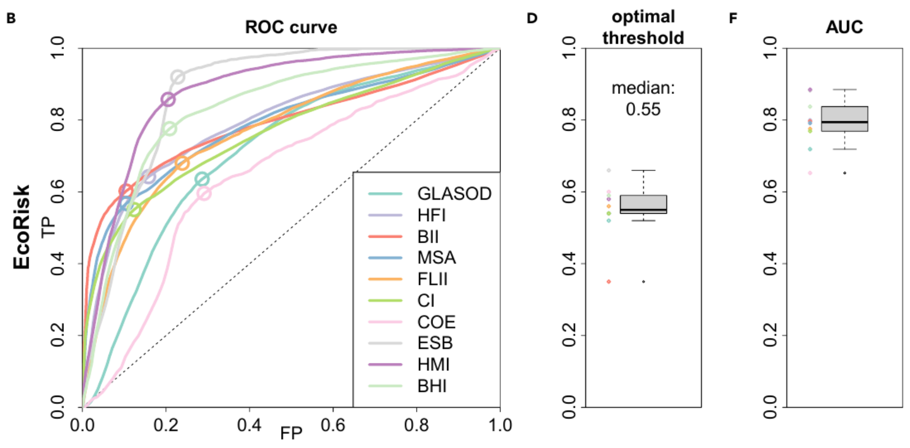


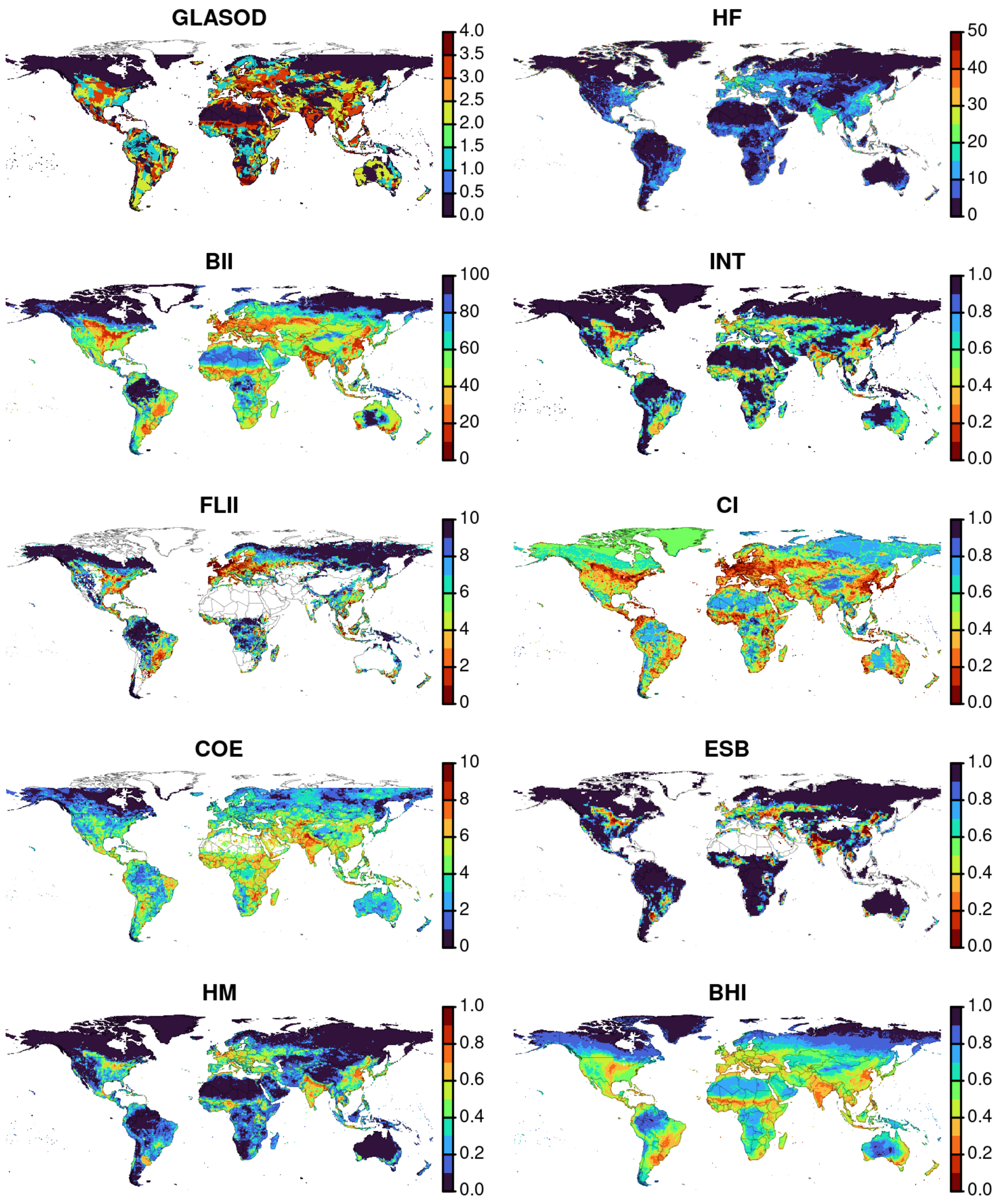
Define thresholds: Comparison with other biosphere integrity indicators

Table A1: Sources for other biosphere integrity indicators and associated degradation thresholds.

Indicator	range	threshold
GLASOD: degree of human induced soil degradation Oldeman et al. (1990)	1–4	strong/extreme: >2 Oldeman et al. (1990)
HFI: human footprint index Venter et al. (2018)	[0,50]	high pressure: >6 Venter et al. (2016)
BII: biodiversity intactness index De Palma et al. (2024)	[0,1]	degraded: <0.9 Newbold et al. (2016), Steffen et al. (2015)
MSA: mean species abundance (GLOBIO 2015) Schipper et al. (2020) `https://portal.geobon.org`	[0,1]	degraded: <0.9 (pers. comm. A. Schipper)
FLII: Forest Landscape Intactness Index Grantham et al. (2020)	[0,10]	low integrity: <7 Grantham et al. (2020)
CI: contextual intactness Mokany et al. (2020b)	[0,1]	high-value: >0.5 Mokany et al. (2020a)
CoE: Convergence of Evidence Cherlet et al. (2018) from World Atlas of Desertification `wad.jrc.ec.europa.eu/geoportal`	[0,10]	many: >7 Cherlet et al. (2018)
ESB: functional biosphere integrity Mohamed et al. (2024)	[0,1]	intact: >0.25 Mohamed et al. (2024)
HMI: Human modification index Kennedy et al. (2019)	[0,1]	high modification: >0.4 Kennedy et al. (2019)
BHI: Biodiversity Habitat Index Harwood et al. (2022)	[0.5,1]	degraded: <0.8 (pers. comm. T. Harwood)

Threshold derived:
0.55





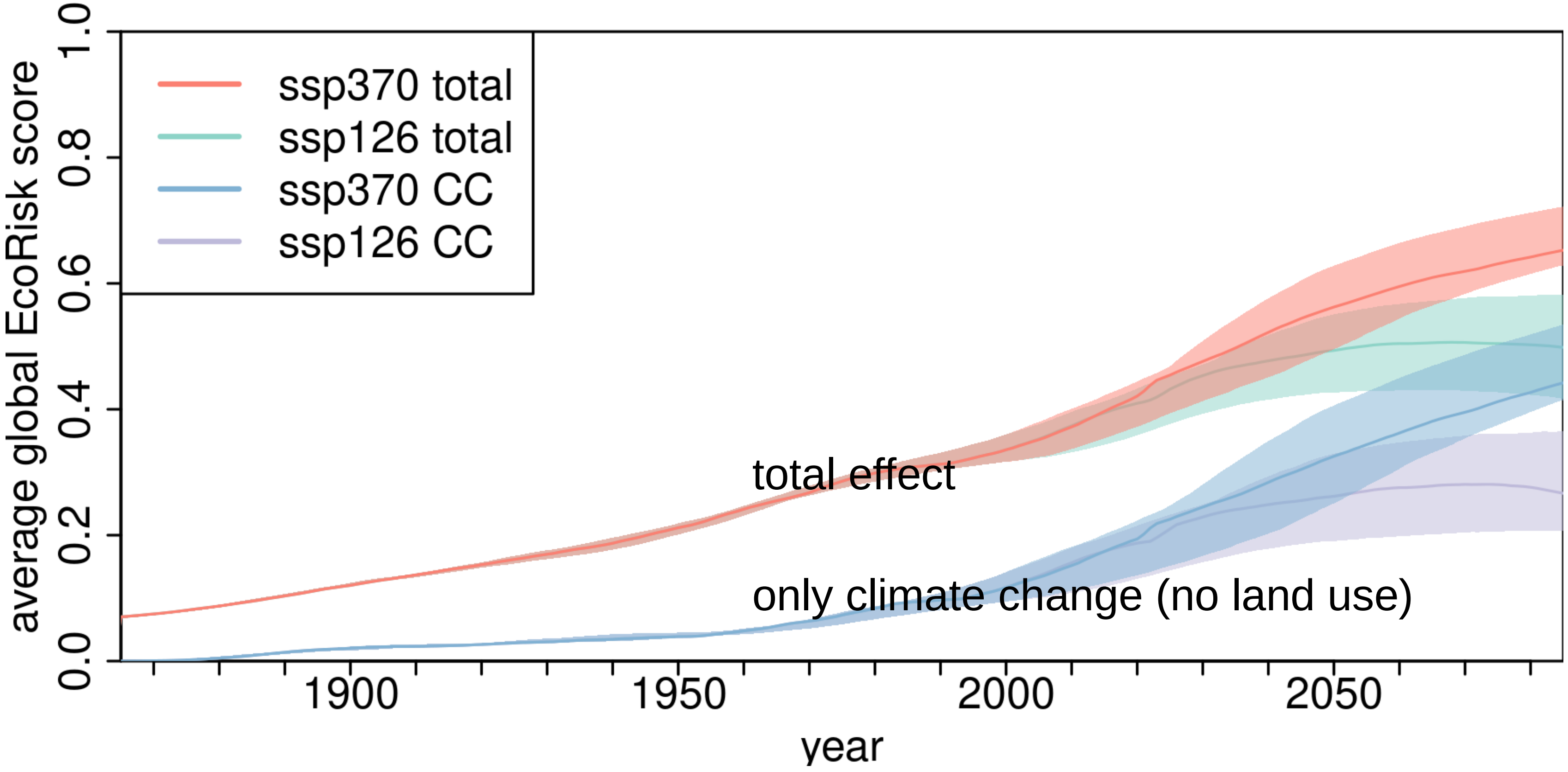
Only in SSP1-26 we might bend the curve

ISIMIP
Inter-Sectoral Impact Model
Intercomparison Project

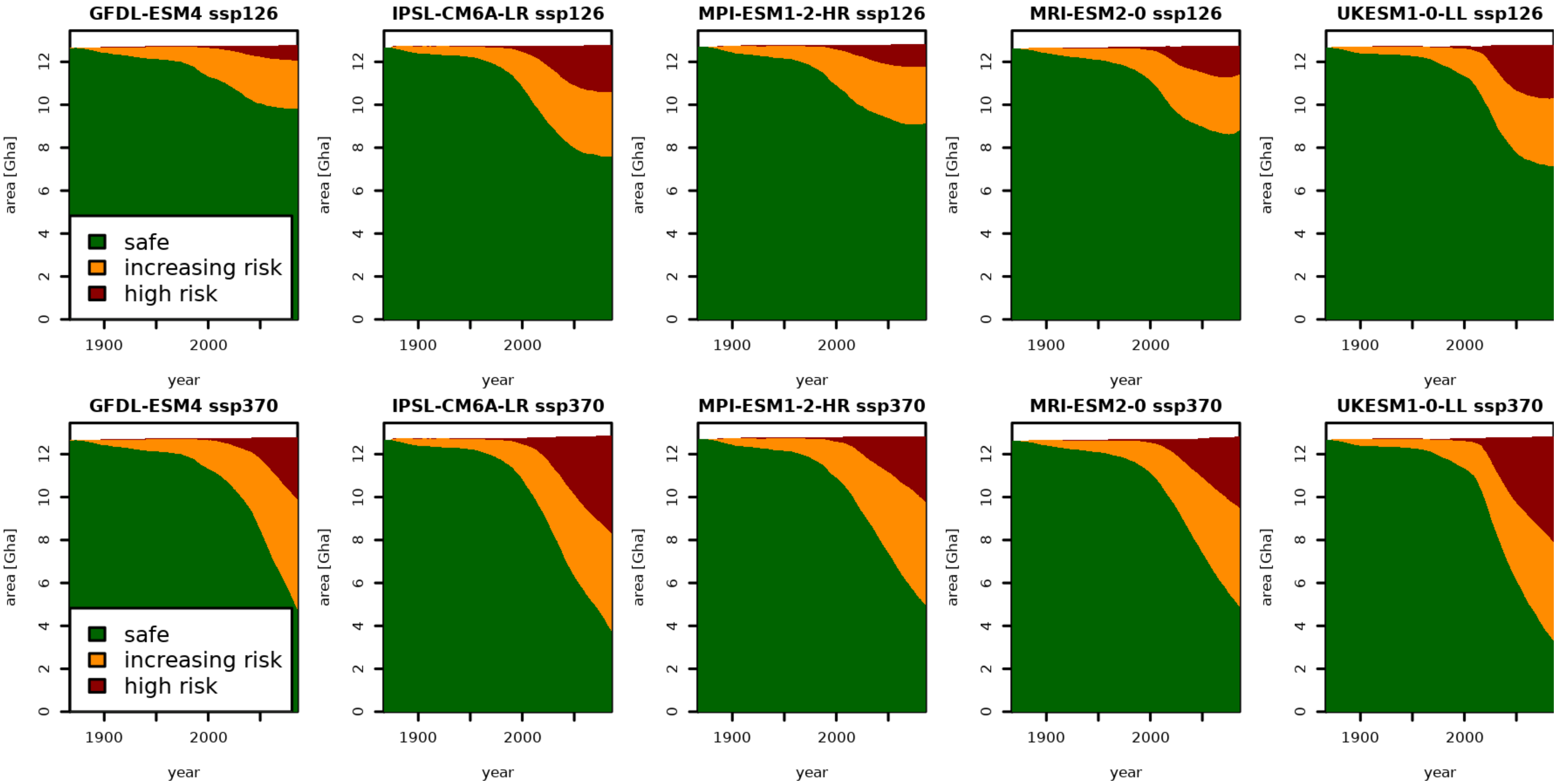
Using ISIMIP3b forcing data in LPJmL (5 GCMs):

- land use (MAgPIE/IMAGE)
- climate (5 GCMs)
- fertilizer (LUH2)

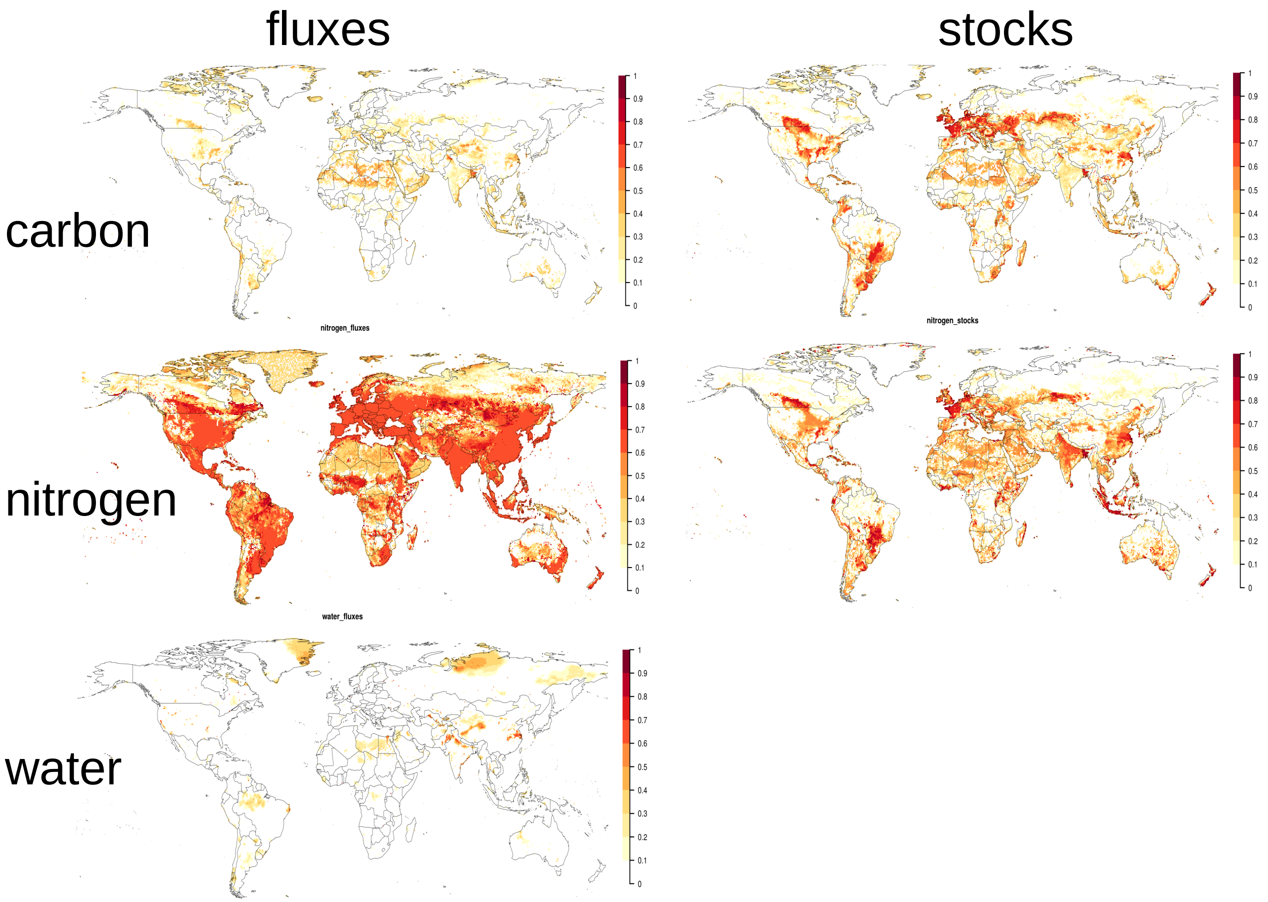
for historical (1850-2015) and future (2016-2100) for several trajectories (SSPs)

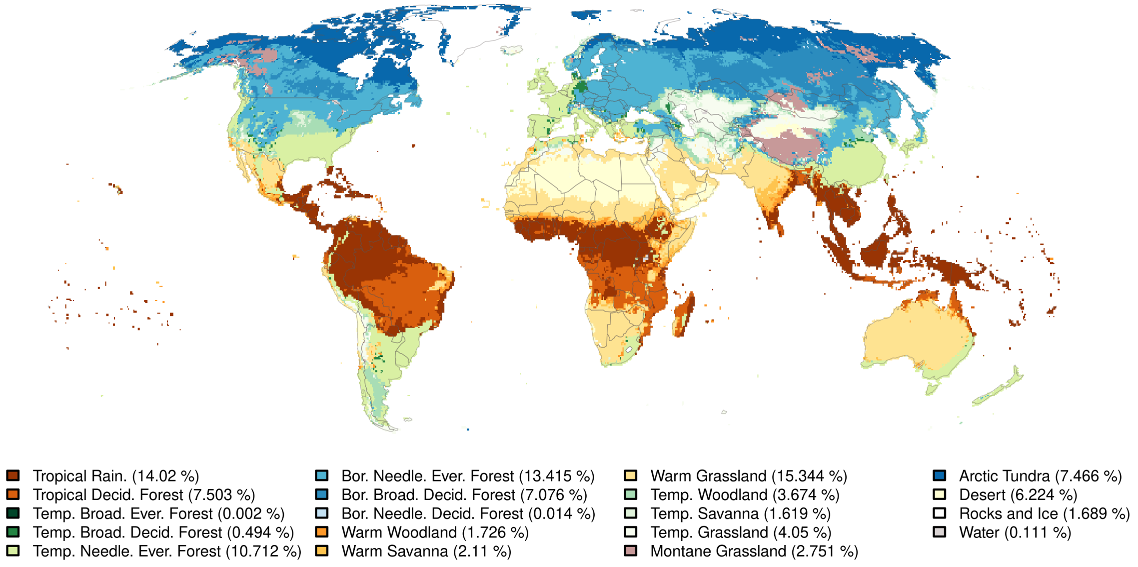


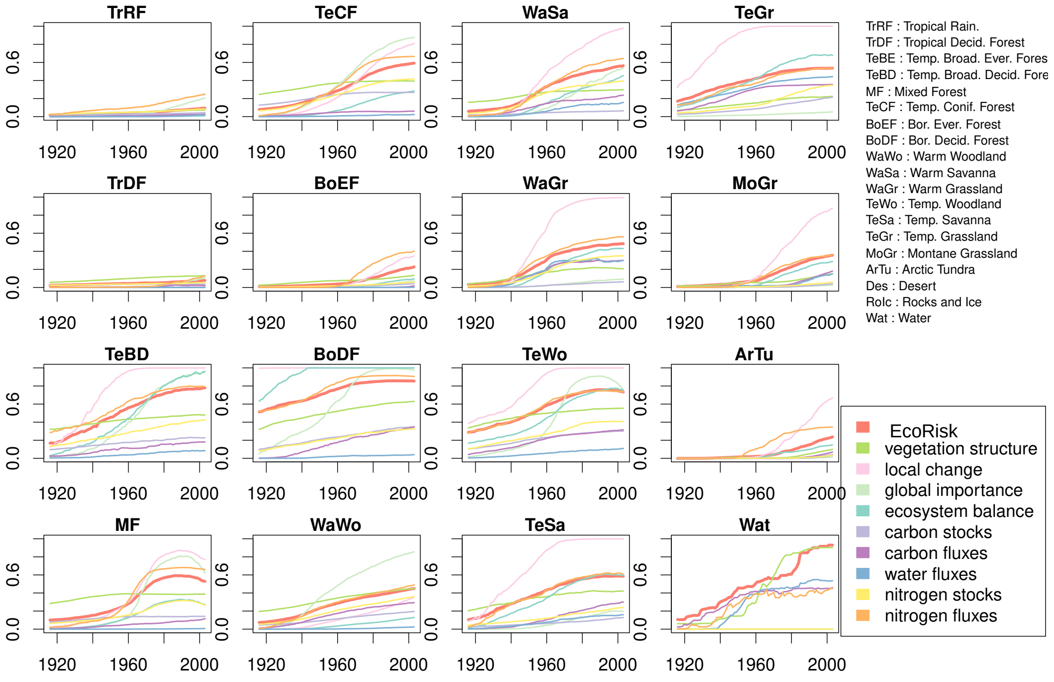
In more detail: Large (mostly) climate dependent variation



EcoRisk as a benchmarking or model testing tool







Conclusion

- EcoRisk is a multidimensional and highly integrative ecosystem change metric
- Complements human pressure based integrity metrics like HANPP or HFI
- Computable for deep past, future based on DGVM outputs
- Can also be used for model benchmarking/testing

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Thank you!

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boundaries
LPJmL

LPJmL

lpjmlkit
LPJmL

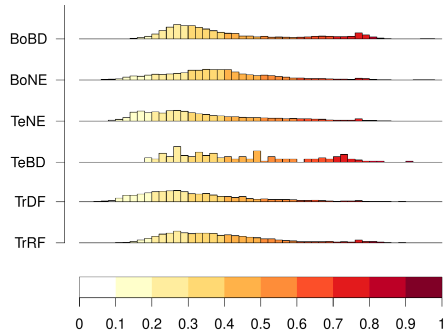
biospheremetrics
LPJmL

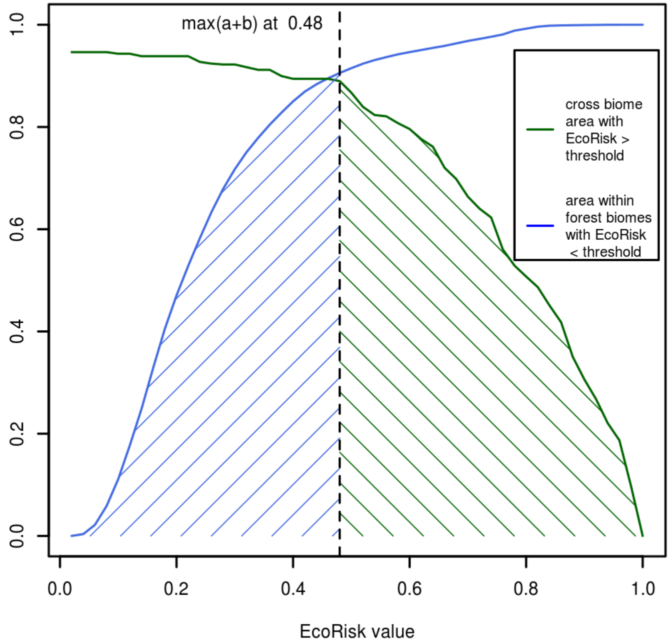
What are suitable thresholds?

EcoRisk: cross biome difference vs. intra-biome heterogeneity analysis suggests 0.5 (0.25 with precautionary distance)

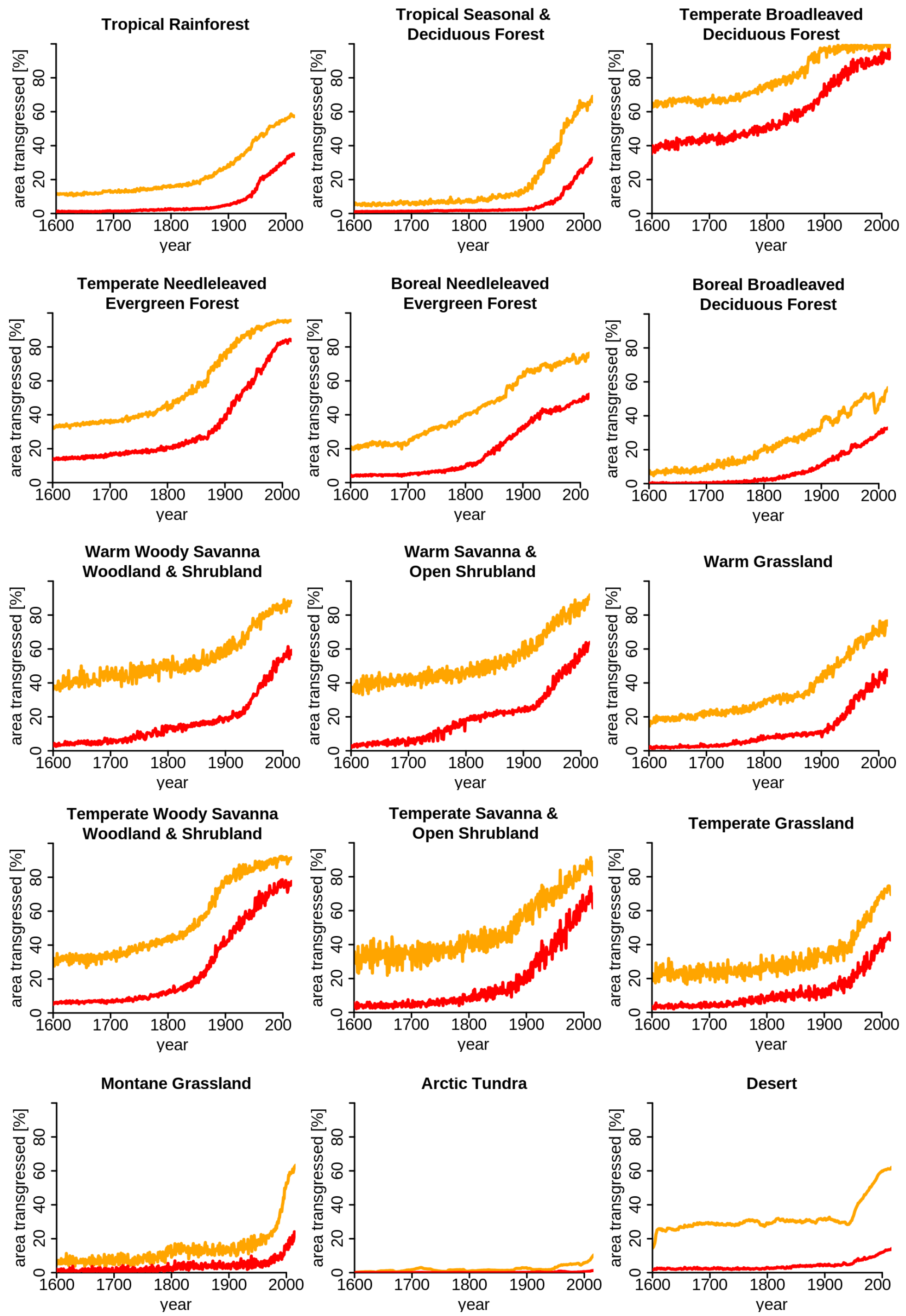
(Stenzel et al. 2024)

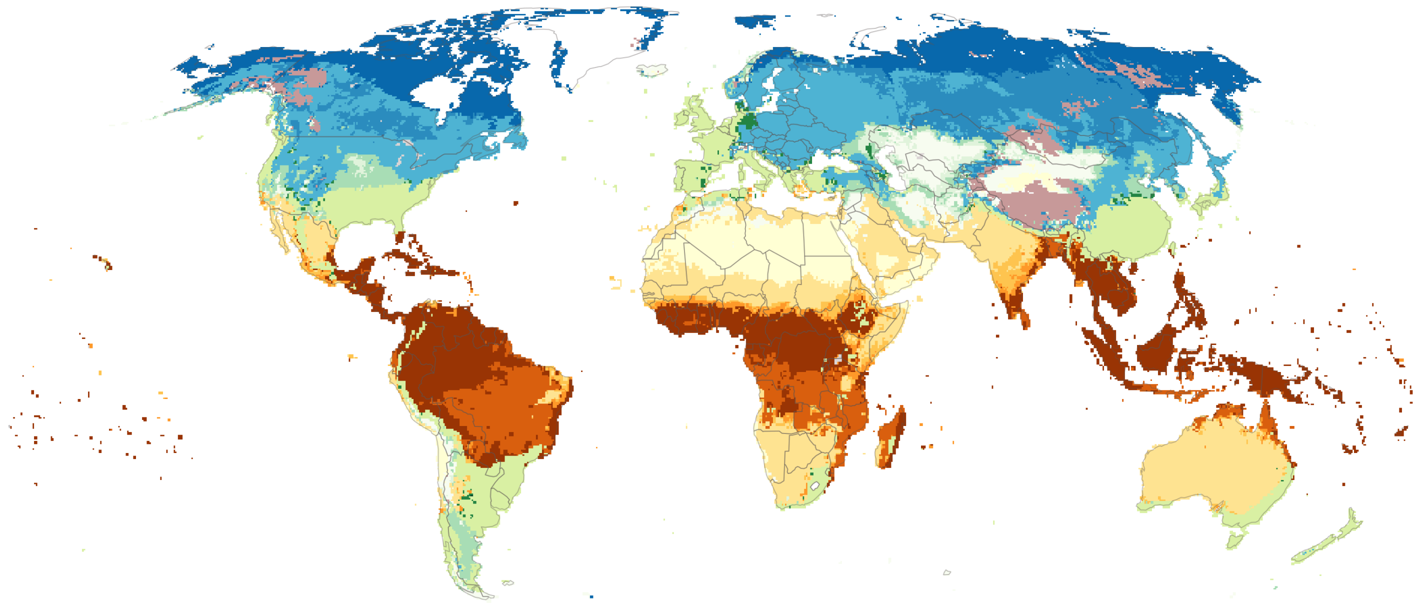
	TrRF	TrDF	TeBD	TeNE	BoNE	BoBD	BoND	WaWo	WaSa	WaGr	TeWo	TeSa	TeGr	MoGr	ArTu	Des
Tropical Rain.	0	0.35	0.88	0.5	0.7	0.83	0.78	0.89	0.92	0.93	0.91	0.92	0.93	0.87	0.88	0.98
Tropical Decid. Forest	0.5	0	0.85	0.72	0.68	0.82	0.77	0.85	0.89	0.9	0.87	0.89	0.9	0.89	0.9	0.98
Temp. Broad. Decid. Forest	0.74	0.72	0	0.62	0.56	0.68	0.82	0.47	0.69	0.66	0.29	0.5	0.82	0.77	0.79	0.93
Temp. Needle. Ever. Forest	0.61	0.62	0.78	0	0.48	0.8	0.79	0.79	0.87	0.88	0.82	0.86	0.88	0.84	0.85	0.98
Bor. Needle. Ever. Forest	0.64	0.63	0.61	0.35	0	0.44	0.76	0.67	0.89	0.89	0.75	0.86	0.89	0.66	0.69	0.97
Bor. Broad. Decid. Forest	0.66	0.67	0.56	0.59	0.32	0	0.67	0.71	0.83	0.84	0.64	0.73	0.91	0.63	0.68	0.96
Bor. Needle. Decid. Forest	0.84	0.83	0.88	0.83	0.79	0.75	0	0.89	0.91	0.91	0.88	0.89	0.9	0.9	0.89	0.96
Warm Woodland	0.76	0.71	0.6	0.71	0.67	0.74	0.83	0	0.68	0.79	0.64	0.72	0.83	0.83	0.86	0.98
Warm Savanna	0.87	0.82	0.56	0.8	0.78	0.81	0.86	0.5	0	0.5	0.45	0.45	0.73	0.78	0.82	0.97
Warm Grassland	0.87	0.85	0.56	0.8	0.79	0.8	0.86	0.67	0.49	0	0.49	0.27	0.36	0.74	0.78	0.8
Temp. Woodland	0.8	0.79	0.2	0.69	0.64	0.72	0.84	0.56	0.57	0.44	0	0.21	0.72	0.73	0.76	0.9
Temp. Savanna	0.86	0.84	0.49	0.77	0.75	0.77	0.81	0.66	0.54	0.18	0.28	0	0.45	0.68	0.72	0.81
Temp. Grassland	0.91	0.9	0.7	0.84	0.85	0.85	0.85	0.81	0.69	0.47	0.64	0.53	0	0.73	0.71	0.84
Montane Grassland	0.87	0.9	0.69	0.77	0.79	0.75	0.9	0.75	0.81	0.78	0.69	0.74	0.8	0	0.41	0.93
Arctic Tundra	0.85	0.89	0.83	0.75	0.76	0.85	0.81	0.87	0.87	0.84	0.8	0.79	0.79	0.46	0	0.88
Desert	0.98	0.98	0.92	0.98	0.97	0.97	0.93	0.98	0.95	0.79	0.88	0.77	0.74	0.86	0.81	0





EcoRisk over time per biome





Tropical Rain. (14.02 %)
Tropical Decid. Forest (7.503 %)
Temp. Broad. Ever. Forest (0.002 %)
Temp. Broad. Decid. Forest (0.494 %)
Temp. Needle. Ever. Forest (10.712 %)
Bor. Needle. Ever. Forest (13.415 %)
Bor. Broad. Decid. Forest (7.076 %)
Bor. Needle. Decid. Forest (0.014 %)
Warm Woodland (1.726 %)
Warm Savanna (2.11 %)
Warm Grassland (15.344 %)
Temp. Woodland (3.674 %)
Temp. Savanna (1.619 %)
Temp. Grassland (4.05 %)
Montane Grassland (2.751 %)
Arctic Tundra (7.466 %)
Desert (6.224 %)
Rocks and Ice (1.689 %)
Water (0.111 %)

Change in vegetation structure (ΔV or v)

Lifeform	Attributes				
Tree:	**Evergreenness**	**Needleleavedness**	**Tropicalness**	**Borealness**	**Naturalness**
TrBE	1	0	1	0	1
TrBR	0	0	1	0	1
TeNE	1	1	0	0	1
TeBE	1	0	0	0	1
TeBS	0	0	0	0	1
BoNE	1	1	0	1	1
BoS	0	0.25*	0	1	1
TrBi	1	0	1	0	0
TeBi	0	0	0	0	0
(attribute weights:	0.2	0.2	0.3	0.3	0.3)

Similar for grasses (incl. crops)

Sum over each ground cover type k (tree, grass, bare soil)

Detailed for each attribute l (evergreenness, tropicalness, ...)

$$V(i,j) = 1 - \sum_k \left\{ \underbrace{\min\left(G_{ik}, G_{jk}\right)}_{total\ area\ of\ GCT\ k} \cdot \left[1 - \sum_l \underbrace{\left(\omega_{kl} \left| \sum_p (A_{iklp} \cdot a_{klp}) - \sum_p (A_{jklp} \cdot a_{klp}) \right| \right)}_{specific\ area\ diff.\ reg.\ attrib.\ l} \right] \right\}$$

Change between state i and j

Local change

NPP_{pi}, $runoff_{pi}$, …, $firef_{pi}$

NPP_{today}, $runoff_{today}$, …, $firef_{today}$

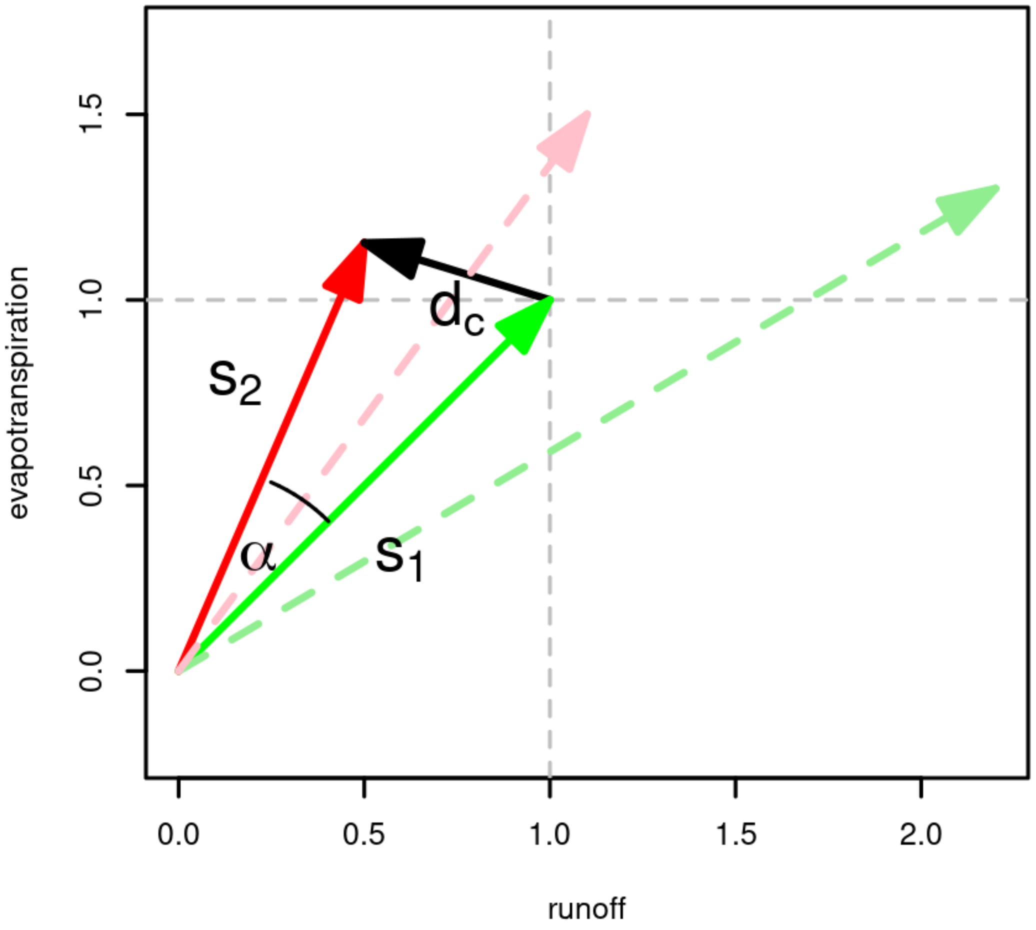
$$\vec{s_1} = \begin{pmatrix} v_{1,1} \\ \vdots \\ v_{n,1} \end{pmatrix}, \vec{s_2} = \begin{pmatrix} v_{1,2} \\ \vdots \\ v_{n,2} \end{pmatrix},$$

scaled by S1
(local reference state – how much have the values changed compared to the reference period e.g. preindustrial = pi)

$$\vec{s_{l_1}} = \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix}, \vec{s_{l_2}} = \begin{pmatrix} v_{1,l} \\ \vdots \\ v_{n,l} \end{pmatrix}$$

$$v_{i,l} = \frac{v_{i,2}}{v_{i,1}}, \quad \text{for } v_{i,1} \neq 0.$$

$$d_c = |\vec{d_c}| = |\vec{s_{l_2}} - \vec{s_{l_1}}|$$



Global change

scaled by global mean value
(global importance – taking into account that even moderate changes on the local scale may feed back to larger scales if large enough in absolute terms)

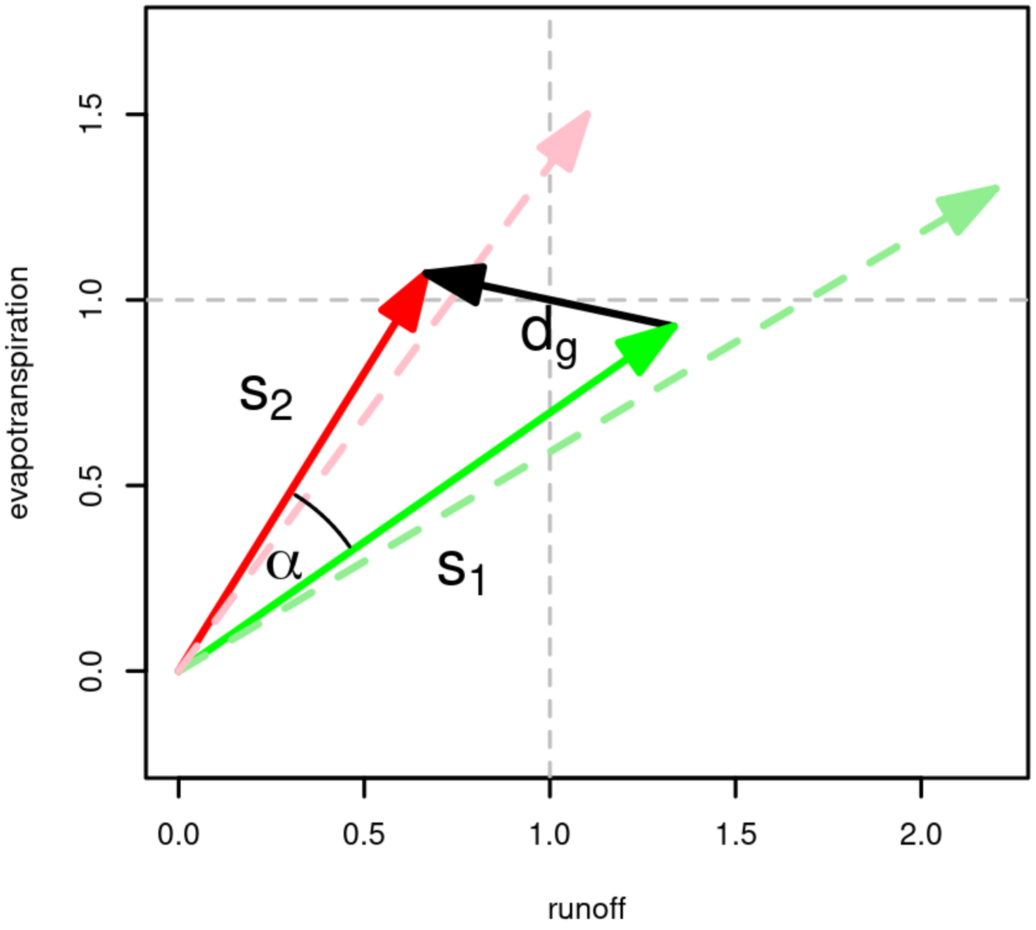
$$\vec{s_1} = \begin{pmatrix} v_{1,1} \\ \vdots \\ v_{n,1} \end{pmatrix}, \vec{s_2} = \begin{pmatrix} v_{1,2} \\ \vdots \\ v_{n,2} \end{pmatrix},$$

$$\vec{s_{g1}} = \begin{pmatrix} v_{1,g,1} \\ \vdots \\ v_{n,g,1} \end{pmatrix}, \vec{s_{g2}} = \begin{pmatrix} v_{1,g,2} \\ \vdots \\ v_{n,g,2} \end{pmatrix}$$

$$v_{i,g,t} = \frac{v_{i,t}}{\overline{v_{i,\mathrm{refg}}}}, \quad \text{for } \overline{v_{i,\mathrm{refg}}} \neq 0$$

$$\overline{v_{i,\mathrm{refg}}} = \frac{1}{\sum a_p} \sum_{p=1}^{z} a_p v_{i,p}$$

$$d_g = |\vec{d_g}| = |\vec{s_{g2}} - \vec{s_{g1}}|.$$

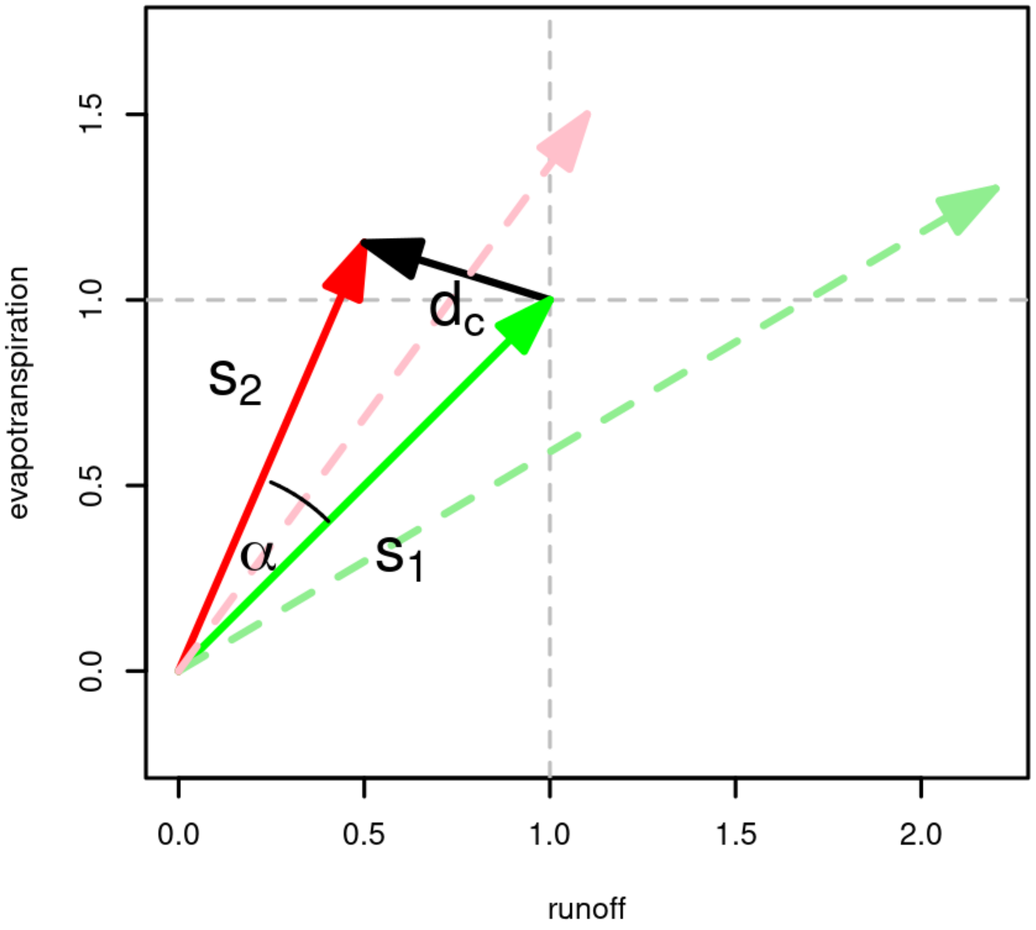


Ecosystem balance

So far only the length of the difference vector was relevant, but also the **angle between the (scaled) state vectors matters**, as it describes shifts with respect to each other

$$b' = 1 - \cos\alpha = 1 - \frac{\vec{s_{l_1}} \cdot \vec{s_{l_2}}}{|\vec{s_{l_1}}||\vec{s_{l_2}}|}.$$

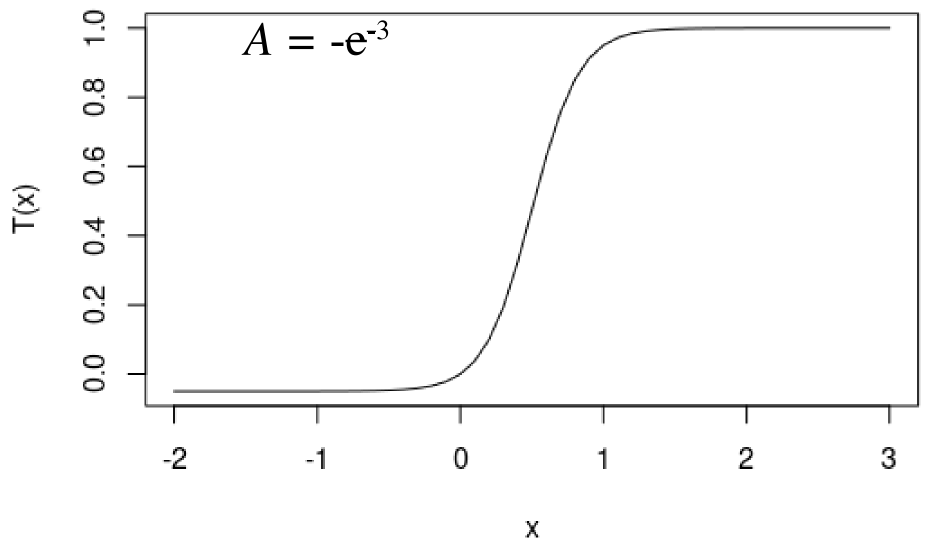
$$b = \begin{cases} b' \cdot 2 & \text{for } \alpha \leq 60° \\ 1 & \text{for } \alpha > 60° \end{cases}$$



Transform to [0,1] + Change to variability ratio

Sigmoid function to transform length of the state diff vector to [0,1].

$$T(x) = A + \frac{1 - A}{1 + \mathrm{e}^{-6(x-0.5)}}$$



- subcomponents are scaled with their change to variability ratio
- (~ signal to noise ratio)
- contains reference variability σ_x
  - high variability in the reference period already → high values for V/g/c/b are scaled down
  - Low variability in the reference period → more weight is put on high values for V/g/c/b

$$S(x, \sigma_x) = \frac{1}{1 + \mathrm{e}^{-4(\frac{x}{\sigma_x} - 2)}}$$