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Respecting the boundaries: balancing climate adaptation and Earth system resilience

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List of abbreviations and acronyms

IPCC	Intergovernmental Panel on Climate Change
IEA	International Energy Agency
WMO	World Meteorological Organisation
WHO	World Health Organisation
UN-Habitat	United Nations Human Settlements Programme
UNEP	United Nations Environment Programme
LCA	Life cycle assessment
GHG	Greenhouse gas
CFC	Chlorofluorocarbon
ODS	Ozone depleting substance
ODP	Ozone depletion potential
HCFC	Hydrochlorofluorocarbon
PB	Planetary Boundary
CC	Climate change (PB)
BI	Change in biosphere integrity (PB)
SO	Stratospheric ozone depletion (PB)
OA	Ocean acidification (PB)
BC	Biogeochemical flows: P and N cycles (PB)
LSC	Land system change (PB)
FW	Freshwater change (PB)
AL	Atmospheric aerosol loading (PB)
NE	Novel entities (PB)

Earth system process / Planetary Boundary	**Control variable(s) for search query**	**# of publications**
Climate change	CO2 OR radiative forcing	3,096
Change in biosphere integrity	Genetic diversity OR HANPP	2,390
Stratospheric ozone depletion	Stratospheric ozone	42
Ocean acidification	Aragonite	25
Biogeochemical flows: P and N cycles	Phosphate OR nitrogen	2,280
Land system change	Forest	7,845
Freshwater change	Freshwater	1,466
Atmospheric aerosol loading	Aerosol	209
Novel entities	Synthetic chemicals	41
		∑ 17,394

Table S1: Control variables for the search queries (TITLE-ABS-KEY (“climate adaptation” AND “control variable xyz”)) and number of publications found.

Climate adaptation option	Primary functional mechanism of adaptation	Direct artificial climate niche	Major ECV group intended to be modified	Major ECV modified
Adaptation of groundwater management	Flow	Yes	Land (Hydrology)	Groundwater
Adapted crops and varieties	Organic	Yes	Land (Biology)	Above-ground biomass
Adaptive management of natural resources	Organic	Yes	Multiple	Multiple
Afforestation and reforestation	Organic	Yes	Land (Biology)	Land cover
Agroforestry	Organic	Yes	Land (Biology)	Land cover
Awareness raising campaigns	Behavioural	Secondarily	Multiple	Multiple
Beach and shoreface nourishment	Flow	Yes	Ocean (Physical)	Sea level
Buildings (also: aircraft, aquatic vessels, rolling stock, vehicles)	Boundary	Yes	Atmosphere (Surface)	Surface temperature
Capacity building	Behavioural	Secondarily	Multiple	Multiple
Cliff strengthening and stabilisation	Boundary	Yes	Ocean (Physical)	Sea level
Climate proofing of buildings against excessive heat	Boundary	Yes	Atmosphere (Surface)	Surface temperature
Climate resilient airports	Multiple	Yes	Multiple	Multiple
Climate resilient electricity transmission, distribution networks and services	Multiple	Yes	Multiple	Multiple
Climate resilient forest management	Organic	Yes	Land (Biology)	Land cover
Climate resilient hydropower systems	Boundary	Yes	Land (Hydrology)	Terrestrial water storage
Climate smart urban agriculture	Organic	Yes	Land (Biology)	Land cover
Climate-Resilient Railway Infrastructure operations and construction	Boundary	Yes	Multiple	Multiple
Clothing	Boundary	Yes	Atmosphere (Surface)	Surface temperature
Coastal wetland restoration	Organic	Yes	Ocean (Physical)	Sea level
Coastal zone management plans	Behavioural	Secondarily	Ocean (Physical)	Sea level
Conservation agriculture	Organic	Yes	Land (Biology)	Soil carbon
Cooling (ambient context)	Flow	Yes	Atmosphere (Surface)	Surface temperature
Crises and disaster management systems and plans	Behavioural	Secondarily	Multiple	Multiple
Desalinisation	Flow	Yes	Land (Hydrology)	Terrestrial water storage
Diversification of tourism	Behavioural	Yes	Multiple	Multiple
Drought and water conservation plans	Flow	Yes	Land (Hydrology)	Terrestrial water storage
Early warning systems	Behavioural	Secondarily	Multiple	Multiple
Early warning systems for vector-borne diseases	Behavioural	Secondarily	Multiple	Multiple
Economic incentives for behavioural change	Behavioural	Secondarily	Multiple	Multiple
Enhancing Ecological Networks	Organic	Yes	Land (Biology)	Land cover
Fire management plans	Organic	Yes	Land (Biology)	Fire
Fisheries and aquaculture diversification	Behavioural	Yes	Ocean (Biological)	Marine habitats
Floating and amphibious housing	Boundary	Yes	Ocean (Physical)	Sea level
Floating or elevated roads	Boundary	Yes	Ocean (Physical)	Sea level
Flood Risk Management Plans	Behavioural	Secondarily	Ocean (Physical)	Sea level
Forest restoration after climate-related disasters	Organic	Yes	Land (Biology)	Land cover
Groynes, breakwaters and artificial reefs	Boundary	Yes	Ocean (Physical)	Multiple
Heat health action plans	Behavioural	Secondarily	Atmosphere (Surface)	Surface temperature
Heating (ambient context)	Flow	Yes	Atmosphere (Surface)	Surface temperature
Improved design of dikes and levees	Boundary	Yes	Ocean (Physical)	Sea level
Improved operational safety at sea	Behavioural	Yes	Ocean (Physical)	Sea level
Improvement of irrigation efficiency	Flow	Yes	Land (Hydrology)	Soil moisture/precipitation
Insurance as risk management tool	Behavioural	Secondarily	Multiple	Multiple
Multifaceted approaches to protecting Tangible Cultural Heritage	Multiple	Yes	Multiple	Multiple
Multi-level and cross-sectoral governance	Behavioural	Secondarily	Multiple	Multiple
Precision agriculture	Organic	Yes	Land (Biology)	Soil carbon
Prevention of climate-related damages to forests	Organic	Yes	Land (Biology)	Land cover
Private-public partnerships (PPPs) for adapting and maintaining infrastructure and services	Behavioural	Secondarily	Multiple	Multiple
Raising and advancing coastal land	Boundary	Yes	Ocean (Physical)	Sea level
Reducing water consumption for cooling of thermal generation plants	Flow	Yes	Land (Human Use of Natural Resources)	Anthropogenic water use
Remote sensing	Behavioural	Secondarily	Multiple	Multiple
Resilient land use planning	Organic	Yes	Land (Biology)	Land cover
Restoration of rivers and floodplains	Organic	Yes	Land (Hydrology)	River discharge
Restoring coastal dunes	Boundary	Yes	Ocean (Physical)	Sea level
Retaining water in rural areas	Organic	Yes	Land (Hydrology)	Soil moisture
Retreat from high-risk areas	Behavioural	Yes	Ocean (Physical)	Sea level
Riparian buffers	Organic	Yes	Land (Hydrology)	River discharge
Risk-based zoning and siting for marine aquaculture	Behavioural	Secondarily	Ocean (Biological)	Marine habitats
Seawalls and jetties	Boundary	Yes	Ocean (Physical)	Sea level
Standards for climate-proof roads	Boundary	Yes	Multiple	Multiple
Storm surge gates and flood barriers	Boundary	Yes	Ocean (Physical)	Multiple
Sustainable infrastructure for livestock health	Multiple	Yes	Multiple	Multiple
Urban green and blue infrastructure	Organic	Yes	Atmosphere (Surface)	Surface temperature
Using water to cope with heat waves in cities	Flow	Yes	Atmosphere (Surface)	Surface temperature
Water restrictions and water rationing	Flow	Yes	Land (Human Use of Natural Resources)	Anthropogenic water use
Water reuse	Flow	Yes	Land (Human Use of Natural Resources)	Anthropogenic water use
Water sensitive forest management	Organic	Yes	Land (Hydrology)	Terrestrial water storage
Water sensitive urban and building design	Boundary	Yes	Land (Hydrology)	Terrestrial water storage
Weather derivatives as risk management tool	Behavioural	Secondarily	Multiple	Multiple

Table S2: Full list of adaptation options considered in the attribution analysis. Table includes a mapping to functional mechanisms of adaptation, soft/hard adaptation, whether artificial spot- or micro-climates are established, and which group of essential climate variables is modified in each case. List of adaptation options based on (Climate-ADAPT, 2026) complemented by key adaptation options from the recent literature on the technosphere component "ambient context" (Galbraith et al., 2025).

Region	2023 energy demand for desalinisation (PJ)	Regional grid carbon intensity factor (g CO_{2e} kWh^{-1})	2023 emissions (Gt CO_{2e})
Middle East	1,690	657.52	0.30
Africa	265	544.76	0.04
Others	69	481.45	0.01
Total	2,024	-	0.35

Table S3: Estimation of 2023 GHG emissions of global desalination. Energy demand based on IEA (IEA, 2024); 2023 grid factors based on Ember Climate (Ember Climate, 2024). Region "others" is assigned to the grid factor for "world." This is likely a lower-bound estimate given the large share of thermal-based desalinisation powered by fossil fuels in the Middle East (IEA, 2023)

2002 ODS demand kt yr^{-1} (unweighted by ODP)				
ODS	**Climate adaptation**		**Other unrelated activities**	**Total**
	Refrigeration	**Foams**	**Medical aerosols, fire protection, …**	
CFC-11	6.0	11.0	3.0	20.0
CFC-12	132.0	1.0	5.0	138.0
CFC-113	0.0	0.0	0.0	0.0
CFC-114	0.0	0.0	0.4	0.4
CFC-115	12.0	0.0	0.0	12.0
Halon-1211	0.0	0.0	3.0	3.0
Halon-1301	0.0	0.0	1.0	1.0
HCFC-22	346.0	7.0	0.3	353.3
HCFC-123	8.0	0.0	0.2	8.2
HCFC-124	3.0	0.0	0.0	3.0
HCFC-141b	0.0	97.0	5.0	102.0
HCFC-142b	0.0	25.0	0.0	25.0
HCFC-225	0.0	0.0	6.0	6.0
Total end-use category unweighted by ODP (kt)	**507.0**	**141.0**	**23.9**	**671.9**
Total end-use category unweighted by ODP (% of total)	**75.45%**	**20.98%**	**3.56%**	**100%**

Table S4: 2002 Demand for ODS unweighted by ODP based on the IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System (2005, p. 408). Totals (by end-use) calculated by the authors.

2002 ODS demand kt yr $^{-1}$ (weighted by ODP)					
ODS	**ODP**	**Climate adaptation**		**Other unrelated activities**	**Total**
		Refrigeration	**Foams**	**Medical aerosols, fire protection, …**	
CFC-11	1.0	6.0	11.0	3.0	20.0
CFC-12	0.8	99.0	0.8	3.8	103.5
CFC-113	0.8	0.0	0.0	0.0	0.0
CFC-114	0.5	0.0	0.0	0.2	0.2
CFC-115	0.5	5.4	0.0	0.0	5.4
Halon-1211	7.1	0.0	0.0	21.3	21.3
Halon-1301	17.0	0.0	0.0	17.0	17.0
HCFC-22	0.0	13.8	0.3	0.0	14.1
HCFC-123	0.0	0.2	0.0	0.0	0.2
HCFC-124	0.0	0.1	0.0	0.0	0.1
HCFC-141b	0.1	0.0	9.7	0.5	10.2
HCFC-142b	0.1	0.0	1.5	0.0	1.5
HCFC-225	0.1	0.0	0.0	0.3	0.3
Total end-use category weighted by ODP (ODP kt)		**124.5**	**23.2**	**46.1**	**193.8**
Total end-use category weighted by ODP (% of total)		**64.23 %**	**11.99 %**	**23.78 %**	**100 %**

Table S5: 2002 Demand for ODS weighted by ODP based on the IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System (2005, p. 408)**; ODP based on (WMO, 2022). ODP for HCFC-225 is the arithmetic average for HCFCs 225 aa-eb. Totals (by end-use) and ODP-weighted ODS demand by category and ODS calculated by the authors.**

	Share of refrigeration and foams of 2002 global ODS demand	**Share of refrigeration and foams of 2002 global ODP-weighted ODS demand**
CFCs	95.07 %	94.61 %
Halons	0.0 %	0 %
HCFCs	97.68 %	96.90 %

Table S6: Share of refrigeration and foams of 2002 global ODS demand unweighted and weighted by ODP (calculated based on Tables S4-S5).

Human climate adaptation and the Planetary Boundary "climate change"

When calculating the **share of climate adaptation-related GHG emissions**, the reference point is most recent total GHG emissions. Most recent global GHG emissions were 53.2 Gt CO_{2e} in 2024 (excluding Land Use, Land-Use Change and Forestry (LULUCF)) (JRC, 2025). CO_2 emissions from LULUCF exhibit more interannual variability and uncertainty; they were estimated at 0.9 Gt CO_{2e} in 2024 (ibid.). In sum, total global GHG emissions in 2024 were therefore 54.1 Gt CO2e in 2024. When calculating the share of annual greenhouse gas emissions related to each functional layer of climate adaptation, the carbon sequestration of organic climate adaptation (0.05 Gt CO2e yr^{-1}) is added to the total emissions of 54.1 Gt CO2e so that the effect of organic climate adaptation can be isolated.

Human climate adaptation and the Planetary Boundary "freshwater change"

The **share of global water withdrawals for desalination** is calculated by dividing the estimate from Jones et al. (2019) of ~3.5×10^1 km^3 yr^{-1} by total annual global freshwater withdrawals of 4.0×10^3 km^3 yr^{-1} (Dorigo et al., 2021). This equals ~0.9 percent. This estimate assumes full operational capacity utilisation and therefore probably constitutes an upper boundary estimate.

Approximations for **annual embodied water in the construction of buildings** was calculated the following. Net additions to gross floor area in buildings in the last years were ~5.0×10^3 km^2 yr^{-1} (UNEP, 2025). Embodied water differs across building type and location. As a rough estimate, median embodied water of ~23.9 m^3 m^{-2} was used by averaging across about a dozen studies from different continents and building types as reviewed in Dixit and Pradeep Kumar (2024). This results in annual embodied water in the construction of buildings of ~1.2×10^2 km^3 yr^{-1}, ~3.0 percent of total annual human freshwater withdrawals of 4.0×10^3 km^3 yr^{-1} (Dorigo et al., 2021). The order of magnitude seems to be right given the global concrete industry alone is responsible for ~1.7 percent of total annual human freshwater withdrawals (Miller et al., 2018). However, the estimate is uncertain given it is unclear how well the building types in the review correspond to the real global split of building types.

Annual embodied water in clothes is approximated from Niinimäki et al. (2020) by deducting irrigation water use for textiles (~4.4×10^1 km^3 yr^{-1}) from the overall water use of the fashion industry (~7.9×10^1 km^3 yr^{-1}), which equals ~3.5×10^1 km^3 yr^{-1}. This equals ~0.9 percent of total annual human freshwater withdrawals.

Human climate adaptation and the Planetary Boundary "stratospheric ozone depletion"

2023 ODP-weighted ODS consumption can be approximated based on the fact that ~100 percent of net global ODS consumption comprises HCFCs (UNEP Ozone Secretariat, 2025) and historical shares of climate adaptation of global ODP-weighted HCFC demand (see Supp. Mat. Table S6). There is no indication that the share of climate adaptation of global ODP-weighted HCFC consumption has decreased recently. If assumed to be constant, climate adaptation would have contributed 96.9 percent of 2023 ODP-weighted ODS consumption.

Relatedly, ODSs do not only disturb stratospheric ozone processes, they can also be considered a special case of novel entities with high global warming potentials. CFCs were developed before stratospheric ozone depletion

and climate change were globally-shared concerns. But they replaced more toxic and more flammable refrigerants such as methyl chloride, methyl bromide, sulphur dioxide or ammonia solutions, which were widely used before (Midgley and Henne, 1930). Later, different applications for ozone depleting substances were found. Optimising for low toxicity and low flammability (e.g., CFC-11) resulted in very high ozone depletion potential, and, incidentally also very high global warming potential (WMO, 2022). Optimising for low ozone depletion potential (e.g., HFC-23) resulted also in very high global warming potential (ibid.). In the last decades, due to the success of the Montreal Protocol, CFCs have gradually been phased-out. However, often CFCs have been replaced by HFCs. Although HFCs have zero ODP, they do exhibit considerable global warming potentials. And interestingly, Velders et al. (2022) show that global HFC emissions are almost exclusively due to climate adaptation.

Analogous to this, asbestos developed for thermal insulation proved to be carcinogenic and was replaced by e.g., polyurethane foams containing ODSs or mineral wool/fiberglass insulation, which for some time also included carcinogenic compounds. The need for considerable climate adaptation to protect communities is undoubted. Yet it is noteworthy that past climate adaptation has in some cases also increased human mortality and morbidity directly or indirectly through e.g., ozone depletion or carcinogenic insulation materials. These examples of maladaptation (Barnett and O'Neill, 2010; Juhola et al., 2016; Schipper, 2020) show that climate adaptation assessments should always including all relevant Earth system variables in the light of a planetary health approach (Myers et al., 2025; Whitmee et al., 2015).

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