Supplementary Material for “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.

Adaptation option	Functional mechanism of adaptation	Soft/hard adaptation	Artifical spot- or microclimate?	Major ECV group modified
Adaptation and diversification of tourism offers	Behavioural	Soft	Yes	Atmosphere (Surface)
Awareness raising campaigns for stakeholders' behavioural change	Behavioural	Soft	Yes	Atmosphere (Surface)
Capacity building on climate change adaptation	Behavioural	Soft	No	Unclear
Crises and disaster management systems and plans	Behavioural	Soft	No	Unclear
Diversification of fisheries and aquaculture products and systems	Behavioural	Soft	Yes	Ocean (Biological)
Early warning systems for vector-borne diseases	Behavioural	Soft	No	Unclear
Economic incentives for behavioural change	Behavioural	Soft	Yes	Unclear
Enhancing operational safety in offshore and inshore operations	Behavioural	Soft	Yes	Ocean (Physical)
Establishment of early warning systems	Behavioural	Soft	No	Unclear
Heat health action plans	Behavioural	Soft	Yes	Atmosphere (Surface)
Retreat from high-risk areas	Behavioural	Soft	Yes	Unclear
Risk-based zoning and siting for marine aquaculture	Behavioural	Soft	Yes	Ocean (Biological)
Adaptation measures to increase climate resilience of airports	Boundary	Hard	Yes	Atmosphere (Surface)
Adaptation options for electricity transmission and distribution networks	Boundary	Hard	Yes	Atmosphere (Surface)
Adaptation options for hydropower plants	Boundary	Hard	Yes	Land (Hydrology)
Beach and shoreface nourishment	Boundary	Hard	Yes	Ocean (Physical)
Cliff strengthening and stabilisation	Boundary	Hard	Yes	Ocean (Physical)
Climate proofed standards for road design, construction and maintenance	Boundary	Hard	Yes	Atmosphere (Surface)
Climate proofing of buildings (against excessive extreme weather)	Boundary	Hard	Yes	Atmosphere (Surface)
Dune construction and strengthening	Boundary	Hard	Yes	Ocean (Physical)
Floating and amphibious housing	Boundary	Hard	Yes	Ocean (Physical)
Floating or elevated roads	Boundary	Hard	Yes	Ocean (Physical)
Groynes, breakwaters and artificial reefs	Boundary	Hard	Yes	Ocean (Physical)
Improved design of dikes and levees	Boundary	Hard	Yes	Ocean (Physical)
Operation and construction measures for ensuring climate-resilient railway infrastructure	Boundary	Hard	Yes	Land (Hydrology)
Raising and advancing coastal land	Boundary	Hard	Yes	Ocean (Physical)
Seawalls and jetties	Boundary	Hard	Yes	Ocean (Physical)
Storm surge gates and flood barriers	Boundary	Hard	Yes	Ocean (Physical)
Textiles for thermal comfort	Boundary	Hard	Yes	Atmosphere (Surface)
Water sensitive urban and building design	Boundary	Hard	Yes	Land (Hydrology)
Adaptation of groundwater management	Flow	Hard	Yes	Land (Hydrology)
Artificial snow production	Flow	Hard	Yes	Atmosphere (Cryosphere)
Cloud seeding	Flow	Hard	Yes	Atmosphere (Atmospheric composition)
Desalinisation	Flow	Hard	Yes	Land (Hydrology)
Heating	Flow	Hard	Yes	Atmosphere (Surface)
Improvement of irrigation efficiency	Flow	Hard	Yes	Land (Hydrology)
Integration of climate change adaptation in drought and water conservation plans	Flow	Hard	Yes	Land (Hydrology)
Reducing water consumption for cooling of thermal generation plants	Flow	Hard	Yes	Atmosphere (Surface)
Refrigeration	Flow	Hard	Yes	Atmosphere (Surface)
Using water to cope with heat waves in cities	Flow	Hard	Yes	Atmosphere (Surface)
Water restrictions and water rationing	Flow	Hard	Yes	Land (Hydrology)
Water reuse	Flow	Hard	Yes	Land (Hydrology)
Adaptation of flood management plans	Multiple	Soft	No	Ocean (Physical)
Improving livestock infrastructure for sustainable food production	Multiple	Hard	Yes	Atmosphere (Surface)
Integration of climate change adaptation in coastal zone management plans	Multiple	Soft	Yes	Ocean (Physical)
Adaptation of fire management plans	Organic	Hard	Yes	Land (Biology)
Adaptive management of natural habitats	Organic	Hard	Yes	Land (Biology)
Afforestation and reforestation as adaptation opportunity	Organic	Hard	Yes	Land (Biology)
Agroforestry	Organic	Hard	Yes	Land (Biology)
Climate resilient forest management	Organic	Hard	Yes	Land (Biology)
Climate smart urban agriculture	Organic	Hard	Yes	Land (Biology)
Conservation agriculture	Organic	Hard	Yes	Land (Biology)
Establishment and restoration of riparian buffers	Organic	Hard	Yes	Ocean (Physical)
Forest restoration after climate-related disasters	Organic	Hard	Yes	Land (Biology)
Improve the functional connectivity of ecological networks	Organic	Hard	Yes	Land (Biology)
Improved water retention capacity in the agricultural landscape	Organic	Hard	Yes	Land (Hydrology)
Integration of climate change adaptation in land use planning	Organic	Hard	Yes	Land (Biology)
Precision agriculture	Organic	Hard	Yes	Land (Biology)
Prevention of climate-related damages to forests	Organic	Hard	Yes	Land (Biology)
Rehabilitation and restoration of rivers and floodplains	Organic	Hard	Yes	Land (Hydrology)
Restoration and management of coastal wetlands	Organic	Hard	Yes	Ocean (Physical)
Urban Green and Blue Infrastructure planning	Organic	Hard	Yes	Atmosphere (Surface)
Use of adapted crops and varieties	Organic	Hard	Yes	Land (Biology)
Water sensitive forest management	Organic	Hard	Yes	Land (Hydrology)
Insurance as risk management tool	Unclear	Soft	No	Unclear
Multifaceted approaches to protecting Tangible Cultural Heritage	Unclear	Soft	No	Unclear
Multi-level and cross-sectoral governance schemes for climate change adaptation	Unclear	Soft	No	Unclear
Private-public partnerships (PPPs) for adapting and maintaining infrastructure and services	Unclear	Soft	No	Unclear
Use of remote sensing in climate change adaptation	Unclear	Soft	No	Unclear
Weather derivatives as risk management tool	Unclear	Soft	No	Unclear

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, 2025) complemented by key adaptation options from the recent literature on the technosphere component "ambient context" (Galbraith et al., 2025) as well as an example of more novel interventions such as cloud seeding (Flossmann et al., 2019).

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 53.21 Gt CO_{2e} in 2024 (excluding Land Use, Land-Use Change and Forestry (LULUCF)) (JRC, 2025). CO2 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 54.11 Gt CO2e in 2024.

Human climate adaptation and the Planetary Boundary "freshwater change"

The **share of global freshwater withdrawals for artificial snow production** is calculated by dividing the estimate from François et al. (2023) for Europe (1.03×10^{-1} km³ yr^{-1}) by total annual global freshwater withdrawals of 4.0×10^{3} km³ yr^{-1} (Dorigo et al., 2021). This equals ~0.003 percent.

The **share of global water withdrawals for desalination** is calculated by dividing the estimate from Jones et al. (2019) of 3.5×10^{1} km³ yr^{-1} by total annual global freshwater withdrawals of 4.0×10^{3} km³ yr^{-1} (Dorigo et al., 2021). This equals ~0.87 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 in the last years were ~5.00×10^{3} km² yr^{-1} (UNEP, 2025). Embodied water differs across building type and location. As a rough estimate, median embodied water of ~23.89 m³ 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 1.20×10^{2} km³ yr^{-1}, 3.00 percent of total annual human freshwater withdrawals of 4.00×10^{3} km³ 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} km³ yr^{-1}) from the overall water use of the fashion industry (7.9×10^{1} km³ yr^{-1}), which equals 3.5×10^{1} km³ yr^{-1}. This equals 0.88 percent of total annual human freshwater withdrawals.

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

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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