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Respecting the boundaries: balancing climate adaptation and Earth system resilience

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Abstract

Anthropogenic climate change necessitates not only rapid climate mitigation but also widespread adaptation. It is common knowledge that climate adaptation cannot replace and must not derail mitigation efforts. Yet surprisingly little is known about the existing pressures of climate adaptation on the Earth system. The Planetary Boundaries framework sets biogeophysical limits for critical Earth system processes. In an explorative analysis, existing interactions of climate adaptation with proxies for the Planetary Boundaries are investigated. Linking research from various domains into an attribution analysis, it is found climate adaptation currently contributes ~25.56 percent of annual greenhouse gas emissions and ~74.08 percent of annual human freshwater withdrawals. Climate adaptation even affects the stratosphere: the ozone hole is to a considerable degree an unintended consequence of climate adaptation. Climate change already drives some of these impacts. However, fuelled by factors such as economic and population growth, the majority of these effects would likely also have occurred under Holocene climates. This proves both the importance and the urgency of respecting safe boundaries when accelerating global climate adaptation.

Keywords

Climate adaptation feedback, Planetary Boundaries, Earth system analysis, resilience, Anthropocene

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Introduction

There is broad scientific consensus that climate mitigation needs to be complemented by widespread climate adaptation (IPCC, 2022a). Even within the limits of the Paris Agreement, hundreds of millions of people have no choice but to adapt to unprecedented climates (Lenton et al., 2023). Because of destabilising Earth system feedbacks, a lack of climate adaptation could also derail societies' ability to stop climate change (Laybourn et al., 2023). Already today the global adaptation gap is large and projections indicate it will continue to widen in the ensuing years (UNEP, 2024, 2025a). While the need for climate adaptation is undisputed, the Earth system is also under intense pressure (Planetary Boundaries Science (PBScience), 2025). The Gaia theory demonstrated how climate adaptation on the level of the biosphere could change the climate and thereby affect the Earth system itself (Lovelock, 1972; Lovelock and Margulis, 1974). Could human climate adaptation have similar effects on the Earth system?

Climate change only really became a problem when the fossil fuel-based metabolism of some industrialised societies expanded globally since the 1950s (Steffen et al., 2007, 2015b). There are structural reasons for this type of scaling behaviour like network effects due to globalisation (Jarvis et al., 2015) and autocatalytic growth processes of niche construction (Ellis, 2015; Galbraith et al., 2025). Therefore, it would not be surprising if the planetary consequences of climate adaptation emerged in a similar manner. Yet given that humans adapt almost exclusively locally to climate change (Berrang-Ford et al., 2021), the systematic assessment of potential climate adaptation-Earth system-interactions is still in its infancy.

Several authors cautioned already more than a decade ago that local climate adaptation might have global environmental impacts (e.g., Eriksen et al., 2011; Adger et al., 2009; Davis and Gertler, 2015). Yet to the best of our knowledge, there is currently no holistic assessment of such impacts covering all relevant Earth system processes and all relevant climate adaptation options. This presents a significant gap in scientific understanding. Some studies investigated potentially extensive hydrological feedbacks from increased climate change-related irrigation (Lobell et al., 2008; e.g., Rosa, 2022). Several others focused on energy-based greenhouse gas (GHG) feedbacks related to climate adaptation but results are partially contradictory. Some authors project strongly increasing energy demand and greenhouse gas emissions due to climate adaptation based on econometric analysis (Van Ruijven et al., 2019). A similar conclusion was reached via a process-detailed integrated assessment model (Colelli et al., 2022). However, a recent study based on specific empirically-derived energy-temperature demand responses reached the opposite conclusion (Abajian et al., 2025). While different modelling frameworks, scopes, and resolutions might explain some of these differences, a recent review aptly summarised that "our response to climate change is by no means obvious, and that different adaptation pathways, more or less energy intensive, are possible." (Viguié et al., 2021, p.16). Addressing this research gap requires a holistic assessment covering all relevant Earth system processes and all relevant climate adaptation options based on a shared framework, scope, and resolution.

Earlier research by the authors (Ott et al., in review) laid the groundwork for this by establishing a purely Earth system-based definition of climate adaptation. This now facilitates the use of established, shared frameworks from Earth system science in order to study the Earth system effects of climate adaptation. One particularly relevant framework for such an assessment is the Planetary Boundaries framework (Rockström et al., 2009; Steffen et al., 2015a; Richardson et al., 2023; Planetary Boundaries Science (PBScience), 2024, 2025). The Planetary Boundaries (PBs) represent thresholds for "nine Earth system processes essential for maintaining global stability, resilience and life-support functions." (Planetary Boundaries Science (PBScience), 2025, p.9). If climate adaptation can be defined from an Earth system-based perspective, it is highly likely that climate adaptation also directly or indirectly interacts with the control variables of the Planetary Boundaries. Yet to the best of our knowledge, these interactions have not yet been studied systematically within the framework of the Planetary Boundaries. This research gap is addressed here. Here, the current state of the Earth system as described by Planetary Boundaries is taken as given and it is approximated how much climate adaptation might be contributing to this very state. This helps establish a common baseline of today's Earth system pressures generated by climate adaptation. Additionally, it could support validation efforts for modelled future projections in other related studies.

Outline and methods

In the first part of this paper (Section 1), our current theoretical understanding of climate adaptation-Earth system-interactions is recapitulated. Potentially relevant interactions of climate adaptation with the control variables of the Planetary Boundaries are identified via screening of >17,000 research articles in the Scopus literature database. For three Planetary Boundaries, relevant and potentially substantial interactions are identified. This subset constitutes the basis for Section 2, where the influence of 70 common climate adaptation options on proxies for the respective control variables is approximated in an attribution analysis. This is done in order to assess today's contribution of human climate adaptation to the current state of these Planetary Boundaries. Following earlier work by the authors (Ott et al., in review), the attribution results are also decomposed into functional layers (socio-metabolic profiles) of climate adaptation and artificial climate niches (areas in which essential climate variables are modified). This helps support policy guidance when it comes to selecting forms of climate adaptation that are compatible with the safe operating space of the Planetary Boundaries. Finally, in Section 3, the drivers of these adaptation-related impacts (climate change vs. other factors such as economic growth) are decomposed in a first approximation before discussing the results (Section 4). This research exemplifies both the importance and the urgency of respecting safe planetary (and Earth system) boundaries when scaling up climate adaptation globally.

1. Climate adaptation and the Earth system: plausible interactions via the Planetary Boundaries

Earlier research by the authors (Ott et al., in review) has already shown how climate adaptation could theoretically affect the Earth system directly. From an Earth system perspective, climate adaptation almost always manifests in what the authors have

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termed *artificial climate niches*: "spatially-confined niches, [in which] essential climate variables are modified significantly, temporarily, and intentionally by humans and for human benefit (ibid., p. 5). For example, the surface air temperature during a heatwave measured inside a well-insulated, air-conditioned building is significantly different from the temperature just outside of this building. Similarly, the soil moisture measured on an irrigated field is significantly different from the soil moisture measured on a non-irrigated, adjacent field. Figure 1 illustrates three different artificial climate niches and some major essential climate variables (ECVs) (GCOS, 2024) modified in each case.

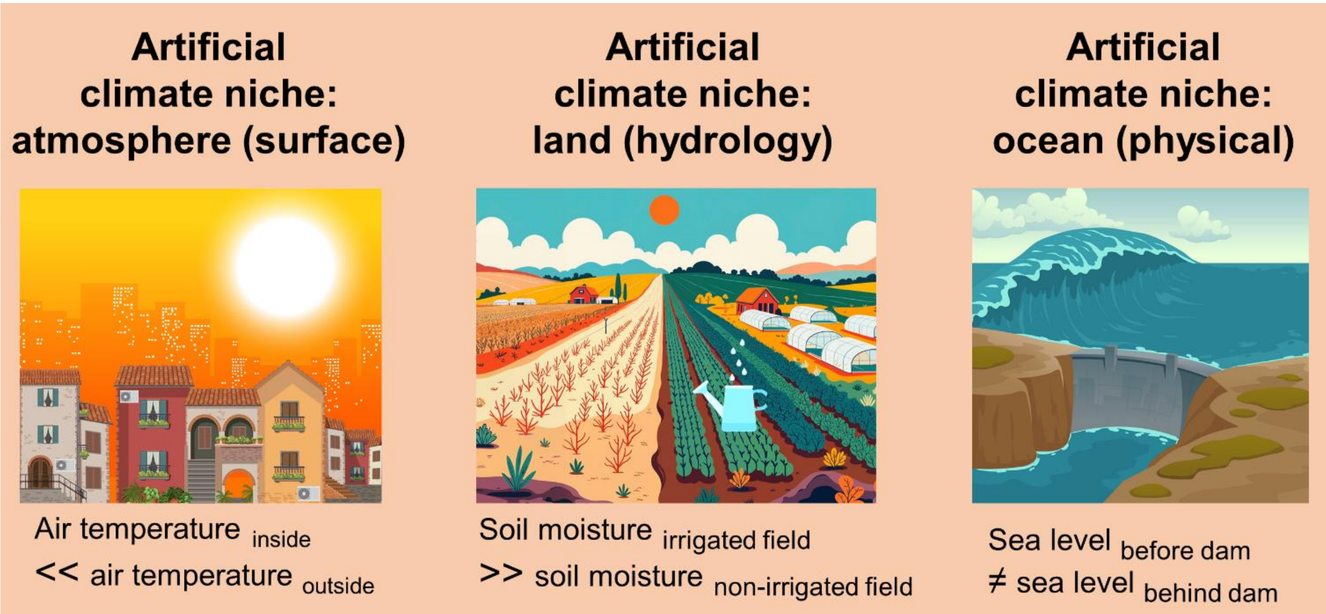

Figure 1: Examples of three artificial climate niches and the respective essential climate variables (ECVs) modified in each case. For details on the concept see Ott et al. (in review).

Importantly, and in line with common Intergovernmental Panel on Climate Change (IPCC) terminology, climate adaptation from an Earth system perspective comprises both adaptation "to actual or expected climate and its effects" (IPCC, 2022c, p.5). The purpose of this study here is to establish a baseline of current Earth system pressures generated by all forms of climate adaptation regardless of why this adaptation has occurred. This broad focus is critical as humans have only started to adapt to anthropogenic climate change in the last decades. In contrast to this, the history of humans acquiring better means of dealing with largely fixed Holocene climates comprises more than 10,000 years. It would therefore not be surprising if large Earth system pressures still result from adaptation to existing climates and only to a smaller degree already from adaptation to anthropogenic climate change.

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When defining climate adaptation from this Earth system-based perspective, the authors (Ott et al., in review) noticed that different forms of climate adaptation can be distinguished functionally from each other by analysing their distinctly different characteristic stocks and flows of energy and matter (socio-metabolic profiles). This facilitates new research directions that could be potentially fairly relevant for policy. So far, detailed bottom-up life cycle assessments (LCAs) are needed to quantify the degree of sustainability of different forms of climate adaptation. In the future, such bottom-up LCAs might be complemented by rapid top-down assessments of the socio-metabolic profiles of different forms of climate adaptation. Four different functional mechanisms of adaptation were defined: *organic*, *behavioural*, *boundary*, and *flow climate adaptation*; detailed definitions and major examples are recapitulated below (Ott et al., in review, p.10):

Functional mechanisms of human climate adaptation: key definitions and examples

- Flow climate adaptation: "Initiation of new flows of energy or matter in order to regulate a certain climate" (e.g., refrigeration, cloud seeding, irrigation or beach nourishment)
- Boundary climate adaptation: "Redirection of existing flows of energy or matter via new spatial boundaries in order to regulate a certain climate" (e.g., buildings, insulation, seawalls)
- Behavioural climate adaptation: "Temporary or permanent relocation to other existing natural/artificial climate niches" (e.g., weather-sensitive behaviour, ecological networks)
- Organic climate adaptation: "Self-sustaining systems that organically regulate a certain climate through their own anatomy/metabolism" (e.g., afforestation, agro-forestry, green roofs and walls)

While orders of magnitudes larger than typical human scales, the authors could show artificial climate niches remain limited at Earth system scales. For instance, the global extent of artificial temperature niches (areas where temperatures are artificially decreased or increased with respect to the direct natural environment) can be estimated at ~0.1 to 0.2 percent of global land area (IEA, 2024; IEA, 2024a). Artificial precipitation niches (areas where precipitation is artificially increased with respect to the direct natural environment), are larger, but with ~3 percent of global land still relatively small (Meier et al., 2018). Local to regional Earth system effects of e.g., extensive irrigation on dry and wet bulb temperatures are evident (Cook et al., 2020; Krakauer et al., 2020; Puma and Cook, 2010; Sacks et al., 2009). Yet at the planetary scale, evidence for direct and substantial climate adaptation-Earth system-interactions is still rather limited.

But what if the effects of climate adaptation on the Earth system mainly occur indirectly via more complex causal chains, that is not via modifying global energy or water fluxes directly? There are many examples for such indirect anthropogenic effects on the Earth system. For instance, fossil fuel combustion results in direct sensible and latent heat fluxes, which are however negligible compared to the influence of combustion-related greenhouse gases on the Earth's energy balance (IEA, 2024; Von Schuckmann et al., 2023). Analogously, human freshwater withdrawals are small compared to the flows in the global hydrological cycle but still result in significant streamflow deviations (Porkka et al., 2024), which in turn can initiate global ecological repercussions (Best, 2019; Reid et al., 2019; Richardson et al., 2023).

The Planetary Boundaries framework has proven it is well-suited to capture the whole range of relevant anthropogenic influences on the Earth system on a common level of resolution. The Planetary Boundaries can be regarded as proxy for the stability and resilience of the Holocene state of the Earth system (Rockström et al., 2009; Steffen et al., 2015a; Richardson et al., 2023). That is, whenever the Planetary Boundaries are transgressed, the risks are high that the Earth's stability and resilience will diminish, which could render the planet into a much less hospitable state for human wellbeing. The purpose of this research here is therefore to investigate whether the increasing transgression of Planetary Boundaries is not independent of, but in fact at least for some boundaries partly driven by human climate adaptation. That is, it is to be investigated how the control variables of the Planetary Boundaries are influenced by climate adaptation. This attribution analysis will only be conducted for the Planetary Boundaries for which a direct functional link of human climate adaptation to the respective control variables can be assumed with a sufficient level of evidence. This selection process, which is a necessary pre-condition for the attribution analysis in Section 2, was conducted in the following manner.

First, >17,000 research articles in the Scopus literature database were screened manually for potentially relevant direct interactions of climate adaptation with the control variables of all Planetary Boundaries (see Supp. Mat. Table S1). Potential direct interactions were found for all Planetary Boundaries with the exception of "ocean acidification." In the next step, for these cases of potential direct interactions, literature was examined for evidence for *substantial* interactions. That is, interactions were searched for that are strong enough to potentially already today result in *substantial influence* of climate adaptation on the respective control variables. Evidence for substantial influence was assigned ranging from "limited" (possible interaction pathway but no clear evidence of global impacts today) to "robust" (interaction pathway demonstrated in the literature and clear evidence of global impacts today). Given the diversity of possible interactions, no single discrete threshold for substantiality was employed. Instead, substantiality is presumed if the interactions are strong enough to elicit policy responses internationally. Additionally, if multiple literature or literature reviews were available, levels of agreement were assigned in line with IPCC terminology (ranging from "low" to "high"). At the end of this selection process, three Planetary Boundaries remained for which substantial direct interactions of climate adaptation with the respective control variables are likely: climate change (CC), stratospheric ozone depletion (SO), and freshwater (FW) change (blue water). However, one should also account for the possibility that direct interactions between climate adaptation and the Planetary Boundaries are amplified by interactions with other Planetary Boundaries. Therefore, further indirect interactions are included if evaluated as of "high" relative importance based on the most recent review of the Planetary Boundaries (Planetary Boundaries Science (PBScience), 2025). Table 1 exhibits the results of this analysis.

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Earth system process / Planetary Boundary (PB)	**Interactions of climate adaptation with Planetary Boundaries**				
	Direct interaction of climate adaptation with control variable(s)	**Most relevant direct interaction identified**	**Degree of confidence for substantial influence on control variable(s) today**	**Literature on current influence (of climate adaptation) on control variable(s)**	**Indirect influence on PB via other PB(s) of "high" relative importance**
Climate change (CC)	X	Substantial greenhouse gas emissions from **refrigeration**	**Robust evidence** Medium agreement	(Abajian et al., 2025; Colelli et al., 2022; Davis and Gertler, 2015; IEA, 2018; UNEP, 2023; Van Ruijven et al., 2019)	BI, LSC
Change in biosphere integrity (BI)	X	Substantial increase in biosphere integrity through **ecological networks for climate migration**	Limited evidence Medium agreement	(Costanza and Terando, 2019; Littlefield et al., 2019; McGuire et al., 2016; Morelli et al., 2020; Saura et al., 2018, 2019)	LSC, AL, CC, NE
Stratospheric ozone depletion (SO)	X	Substantial emissions of ozone depleting substances from **refrigeration and insulation**	**Robust evidence** High agreement	(Daniel et al., 2007; Lickley et al., 2020; Statt, 1988)	-
Ocean acidification (OA)	-	-	No evidence	-	CC
Biogeochemical flows: P and N cycles (BC)	X	Substantial reduction of global synthetic fertiliser consumption due to **climate-resilient agriculture**	Limited evidence Medium agreement	(Lu and Tian, 2017; Rockström et al., 2025; Young et al., 2021)	-
Land system change (LSC)	X	Substantial contribution of **urban reforestation** to global forest cover	Limited evidence High agreement	(Sims et al., 2025; Teo et al., 2021)	FW, BI, CC
Freshwater change (FW)	X	Substantial contribution of **irrigation** to global freshwater withdrawals	**Robust evidence** High agreement	(Campbell et al., 2017; McDermid et al., 2023)	CC
Atmospheric aerosol loading (AL)	X	Substantial contribution of **stratospheric aerosol injection** to global aerosol emissions	Limited evidence High agreement	(Klimont et al., 2017; Smith et al., 2011; Vattioni et al., 2025)	AL, NE
Novel entities (NE)	X	Substantial reduction of global synthetic pesticide consumption due to **climate-resilient agriculture**	Limited evidence Medium agreement	(FAO, 2025; Möhring et al., 2025; Rockström et al., 2025)	-

Table 1: Mapping of Earth system processes/Planetary Boundaries (PBs) to possible direct interactions of climate adaptation based

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on literature screening. Indirect influence on PBs via other PBs is included if evaluated as of "high" relative importance based on the most recent review of the Planetary Boundaries (Planetary Boundaries Science (PBScience), 2025).

Employing these results, different forms of climate adaptation resulting in different artificial climate niches can now be mapped to the Planetary Boundaries. Furthermore, the potential influence of climate change on the Planetary Boundaries via different forms of climate adaptation can be shown. Figure 2 includes all Planetary Boundaries for which direct, substantial interactions with climate adaptation were found above as well as all indirect interactions with these boundaries if they are of "high" relative importance.

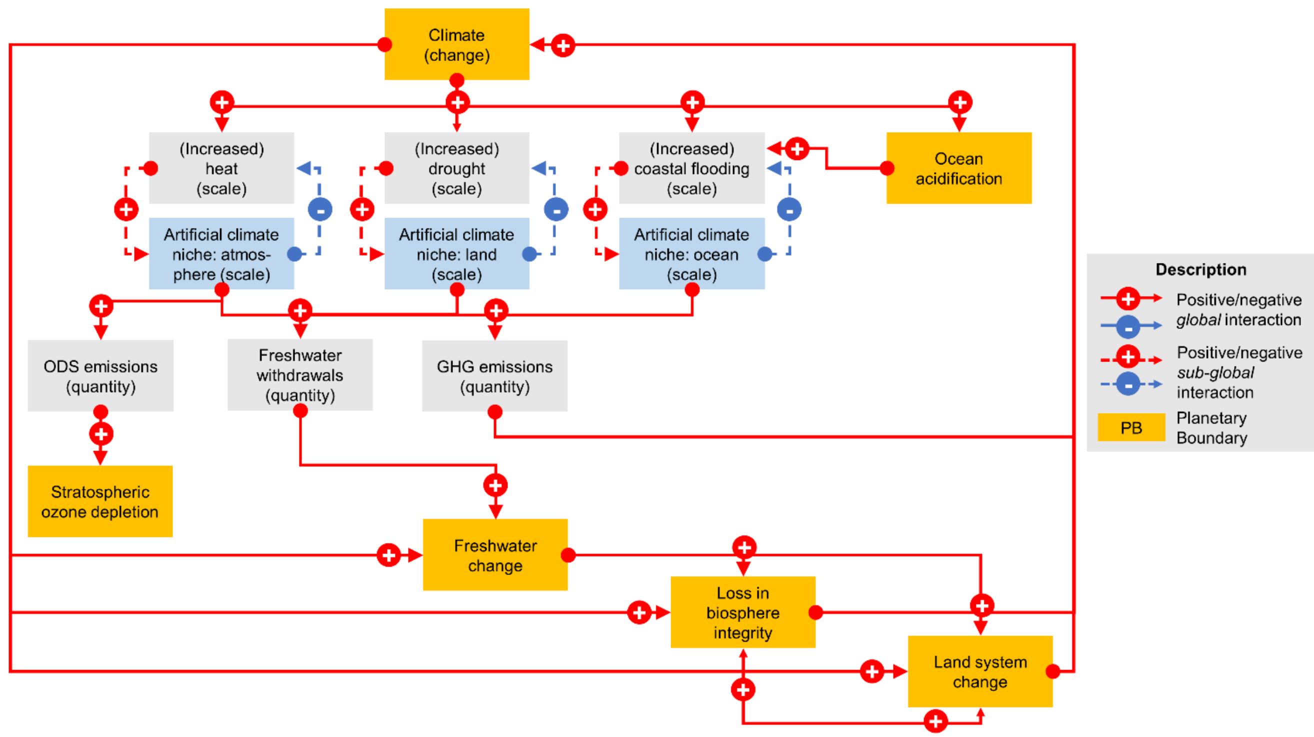

Figure 2: Plausible interactions of climate adaptation with Planetary Boundaries based on literature review. Positive (amplifying) interactions in red and negative (dampening) interactions in blue. Dashed lines indicate sub-global instead of global interactions. Note: not all interactions with all Planetary Boundaries shown for reasons of conceptual clarity. Indirect interactions between Planetary Boundaries included if assessed as of "high" relative importance in the most recent Planetary Health Check (Planetary Boundaries Science (PBScience), 2025). Interactions between climate change and artificial climate niches based on Ott et al. (in review). Influence of ocean acidification on increased coastal flooding based on Beck et al. (2018).

Figure 2 reveals not only interactions but importantly also several feedback loops. In theory, most feedbacks of human climate adaptation on the Earth system at the planetary scale are likely to be positive (self-reinforcing) and therefore potentially destabilising. For instance, climate change precipitates a growing scale of the artificial climate niche "atmosphere" through e.g., enhanced air-conditioning, which results in household-level cooling but local (Salamanca et al., 2014) and global warming (UNEP, 2023). The only likely negative (attenuating) feedbacks of artificial climate niches only occur on local to regional scales, such as decreased dry bulb surface air temperatures due to irrigation in artificial land (hydrology) niches. The direction

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of some interactions and hence feedbacks is still unclear. Additionally, no indirect interactions of "medium" or "low" importance were analysed here. Yet Fig. 2 already illustrates potentially far-reaching effects of climate adaptation on a whole range of different, vital Planetary Boundaries. In Section 2, an exploratory attribution analysis will now be conducted to calculate how strong these interactions for all direct and potentially substantial cases (CC, FW, and SO) really are.

2. Climate adaptation and the Planetary Boundaries

Following earlier research by the authors on the direct Earth system impacts of climate adaptation (Ott et al., in review), this attribution analysis here comprises all major adaptation options from the Climate-ADAPT database (Climate-ADAPT, 2025) as of December 2025. This database is one of the most comprehensive available and is regularly used by policymakers as well as researchers. The adaptation options in this database are complemented by key forms of adaptation from the recent literature on the technosphere component "ambient context" (Galbraith et al., 2025) as well as by an example of more novel interventions such as cloud seeding (Flossmann et al., 2019). The full list of these 70 different forms of climate adaptation and the mapping to corresponding functional mechanisms of adaptation and artificial climate niches can be found in Suppl. Mat. Table S2. For each of the selected Planetary Boundaries, the impact of different forms of climate adaptation on the respective proxies for the control variables is decomposed into functional mechanisms of adaptation and artificial climate niches. On a cautious note, not for all forms of climate adaptation literature on relevant impacts could be found. The estimates here therefore present a cautious, lower-boundary.

2.1. Human climate adaptation and the Planetary Boundary "climate change"

For the Planetary Boundary "climate change," there are currently two control variables: atmospheric CO_2 concentration and total anthropogenic radiative forcing at the top of the atmosphere (Richardson et al., 2023). Precisely calculating the current influence of human climate adaptation on this Planetary Boundary would involve processing all greenhouse gas (GHG) emissions related to climate adaptation in an Earth system model. In order to avoid excessive complexity, a high-resolution proxy is used instead: most recent GHG emissions. A reasonably close proximity between this proxy and the influence on the two respective control variables can be assumed.

2.1.1. Flow climate adaptation

Cooling-related GHG emissions were estimated at 4.09 Gt CO_{2e} in 2022 (UNEP, 2023). Heating-related GHG emissions were estimated at 4.16 Gt CO_{2e} in 2022 (IEA, 2024d). According to a recent study, current annual GHG emissions of irrigation (related to energy used for pumping and outgassing from groundwater) can be estimated at 0.22 Gt CO_{2e} (Qin et al., 2024). GHG emissions related to global desalination can be approximated to be ~0.35 Gt CO_{2e} (see Supp. Mat. Table S3); depending on modelling assumptions, present emissions could be slightly higher (Rosa et al., 2026) or lower (Magni et al., 2025). Global

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GHG emissions from artificial snow production seem to be negligible (~10^{-4} Gt CO_{2e}), at least based on regional studies for Europe (François et al., 2023).

2.1.2. Boundary climate adaptation

Annual embodied GHG emissions related to the construction and refurbishment of buildings were estimated at 2.16 Gt CO_{2e} in 2019 (IPCC, 2022b, p.963). Apparently little has changed since then (UNEP, 2025b) but some integrated assessment models calculate with even higher numbers (Zhong et al., 2021). Clothing-related GHG emissions were estimated at 2.90 Gt CO_{2e} in 2019 (Niinimäki et al., 2020)**.** This is a conservative estimate as it excludes inter alia the use-phase of clothes, which is essential for maintaining the desired climate adaptation effect. Total annual embodied emissions in irrigation infrastructure are currently unclear but potentially non-negligible due to e.g., large reservoir dams supporting irrigation (Keller et al., 2021; Song et al., 2018). Similarly, embodied emissions in coastal protection infrastructure as well as direct and indirect ecosystem-based emissions through e.g., dredging can be substantial (Nieuwkamer et al., 2022) but are still uncertain at the global scale.

2.1.3. Behavioural climate adaptation

A certain part of tourism-related GHG emissions could be accounted for as behavioural climate adaptation but if and only if a significant climate difference is the critical motivation for these travels (e.g., “coolcation”). For instance, in some regions of Europe, there is a long history of people in physical distress spending time in climate health resorts (German: “heilklimatische Kurorte”). Furthermore, anecdotally, there are strong tourist flows from continental areas to the sea side especially during summer. Nonetheless, substantial parts of global travel are probably conducted irrespective or even despite of pronounced climatic differences (e.g., business travel, winter sports vacation, city travel). It is unclear for which parts of tourism a significant climate difference is the critical motivation. Therefore, although substantial at the global scale (Sun et al., 2024), tourism-related emissions will as of yet not be accounted for here. There might also be additional emissions due to local climate-related changes in mobility patterns (Obradovich and Rahwan, 2019; Yücel et al., 2025) yet they are uncertain at the global scale. Emissions related to climate migration are also uncertain.

2.1.4. Organic climate adaptation

Estimating the GHG emissions/sequestrations of organic climate adaptation is also challenging. Many nature-based forms of climate adaptation sequester CO_2, especially but not exclusively in coastal areas (Barbier et al., 2011; Chmura et al., 2003; Morris et al., 2018; Song et al., 2023). Yet while e.g., seagrass, mangroves or salt marshes protect coastal areas organically from extreme flooding, many of these areas have been intentionally destroyed instead of intentionally established by humans. Despite considerable political action, recent assessments show many of these valuable ecosystems are still in decline and often suffer from degradation (Convention on Wetlands, 2025). For mangroves, for example, natural regrowth and forestation have

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decreased but not out-paced deforestation rates (Friess et al., 2019; Richards et al., 2020). At least for urban forests an estimate of sequestered carbon can be inferred from Teo et al. (2021): 0.05 Gt CO_{2e} yr^{-1}.

Table 2 shows an overview of the four functional layers of human climate adaptation and the artificial climate niches matched to the corresponding adaptation options and their estimated annual GHG emissions. As discussed above, this is a lower-bound estimate as the GHG emissions of many relevant categories cannot yet be reliably estimated. That is, in reality the climate adaptation-Earth system-interactions in terms of climate change will probably be even stronger than estimated here.

Functional layer of climate adaptation	**Type of artificial climate niche (major group of ECVs modified)**	**Climate adaptation form**	**Annual GHG emissions (in most recent Gt CO_{2e})**	**Source**
Flow climate adaptation	**Atmosphere**	Artificial cooling	4.09	Based on (UNEP, 2023)
		Artificial heating	4.16	Based on (IEA, 2024d)
	Atmosphere / Land	Irrigation	0.22	Based on (Qin et al., 2024)
	Land / Ocean	Desalination	~0.35	Calculated based on (IEA, 2024e) and 2023 grid factors from (Ember Climate, 2024).
Boundary climate adaptation	**Atmosphere**	Embodied emissions in buildings	2.16	Based on (IPCC, 2022b, p.963)
		Clothing	2.90	Based on (Niinimäki et al., 2020)
	Land / Ocean	Embodied emissions in blue infrastructure and coastal protection	+ ?	Unclear at the global scale
Behavioural climate adaptation	**Atmosphere / Land / Ocean**	Effects of e.g., climate-related tourism, temporary relocation, behavioural change etc.	+ ?	Unclear at the global scale but potentially non-negligible (Sun et al., 2024; Obradovich and Rahwan, 2019)
Organic climate adaptation	**Land**	Urban forests	- 0.05	Inferred from (Teo et al., 2021).

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	Atmosphere / Land / Ocean	Various other nature-based adaptation solutions	± ?	Unclear at the global scale but potentially non-negligible (Barbier et al., 2011; Chmura et al., 2003; Morris et al., 2018; Richards et al., 2020)
Total			**~13.83 Gt CO_{2e}**	

Table 2: Functional layers of human climate adaptation, artificial climate niches, and estimated global annual GHG emissions from major corresponding adaptation options.

In summary, annual GHG emissions related to human climate adaptation currently equal approximately 13.83 Gt CO_{2e}. This implies ~25.56 percent of most recent global annual GHG emissions (see Supp. Mat.) are related to human climate adaptation. Figure 3 shows how these shares related to human climate adaptation are distributed across functional layers of adaptation. The contribution of flow climate adaptation is almost twice as strong as the contribution of boundary climate adaptation. And although considerable uncertainties remain, the carbon sinks related to organic climate adaptation appear too small to compensate for the considerable carbon sources related to flow and boundary climate adaptation. This provides first evidence of the substantially different impact different functional mechanisms of climate adaptation can have on the Earth system.

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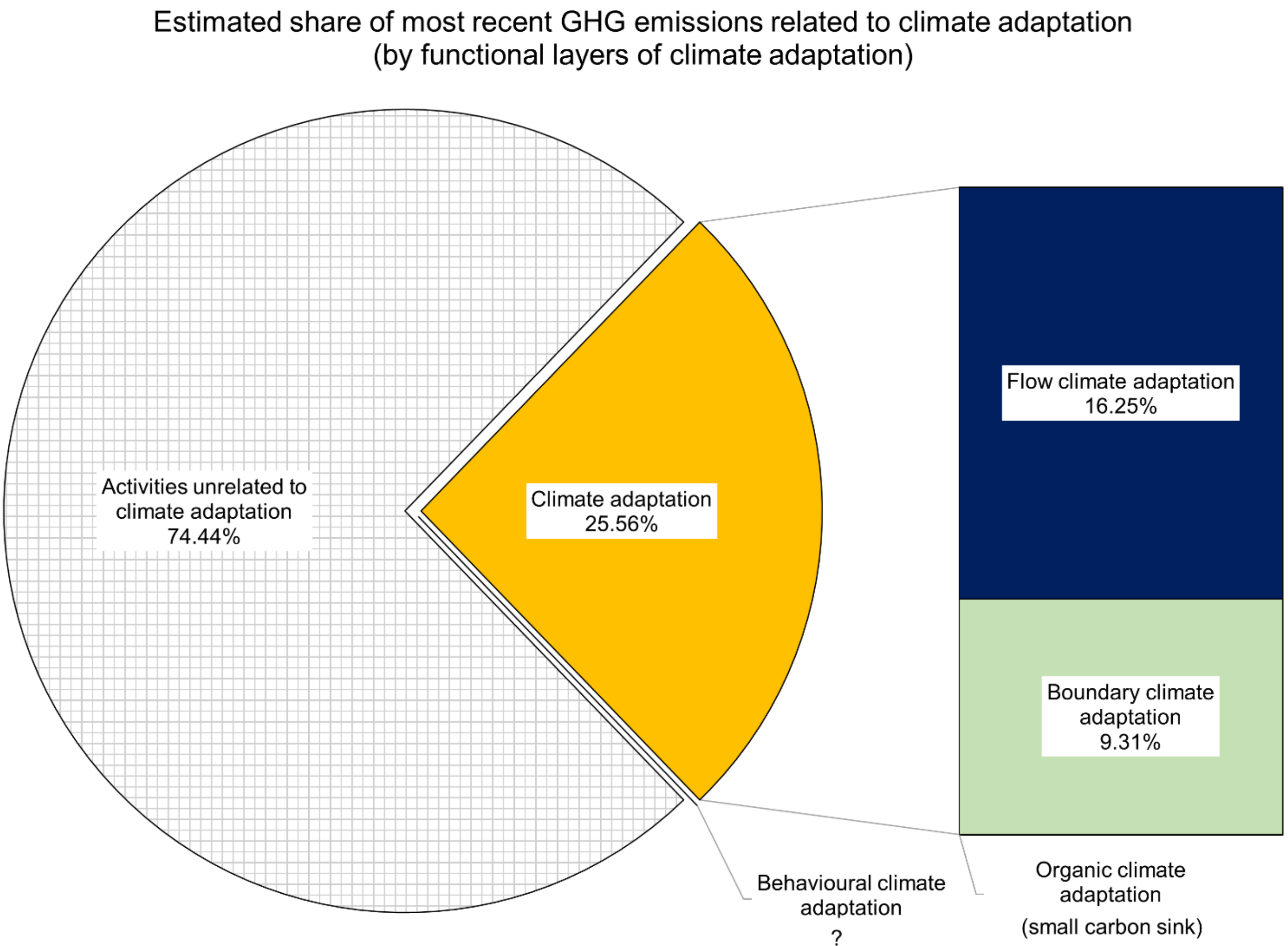

Figure 3: Estimated share of annual GHG emissions related to climate adaptation (by different functional layers of climate adaptation). Approximately 25.56 percent of most recent annual GHG emissions are related to climate adaptation. If it was not for organic climate adaptation, a small carbon sink, this share would be 0.09 percentage points higher. About 2/3 of the overall contribution of climate adaptation comes from flow climate adaptation and 1/3 from boundary climate adaptation. The effect of behavioural climate adaptation is still unclear at the global scale.

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

The control variable of the Earth system process "stratospheric ozone depletion" is set as the globally-averaged stratospheric O_3 concentration as expressed in Dobson units (DUs); the respective Planetary Boundary at a <5 percent reduction from pre-industrial levels (Rockström et al., 2009; Steffen et al., 2015a; Richardson et al., 2023). The current state of the stratospheric O_3 concentration is a result of various physical and chemical processes but has been mostly disturbed by novel entities (ozone depleting substances; ODSs) released by human activities (Molina and Rowland, 1974). Therefore, this attribution analysis will focus solely on the consumption of ODSs as a proxy for the difference between the pre-industrial globally-averaged

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stratospheric O_3 concentration and the current state. When isolating the current contribution of climate adaptation to this proxy, the proportion of ODSs used in refrigeration, air conditioning or insulation foams to overall ODS emissions needs to be estimated and isolated from other uses like solvents, fire extinguishers or cleaning agents.

2.2.1. Flow and boundary climate adaptation

The first generation of ODSs manufactured at the industrial scale was comprised of chlorofluorocarbons (CFCs) such as CFC-11 or CFC-12. These compounds were explicitly invented as refrigerants (Midgley and Henne, 1930). Refrigerants are used in refrigerators, freezers, air conditioners, and heat pumps – prime examples of flow climate adaptation. Many ODSs controlled by the Montreal Protocol have at least partly been used as refrigerants. While the production of most ODSs has been banned or at least phased-out by the Montreal Protocol, there is a large number of existing ODS banks which are almost exclusively comprised of climate adaptation technologies like insulations foams, refrigerators, and air conditioners (Lickley et al., 2020). But what exactly is the current contribution of climate adaptation to stratospheric ozone depletion?

In a first approximation, global ODS consumption is considered. Different sources are combined in order to estimate the contribution of climate adaptation to ODS consumption in different years. In 1974, the global share of ODSs consumed for climate adaptation (refrigeration and blowing agents for foams) amounted to ~30 percent; this figure increased to ~60 percent in 1986 and even further to ~85 percent in 1996 (Daniel et al., 2007). In 2002, 96.43 percent of global ODS demand (which in contrast to ODS consumption excludes ODS destruction) came from refrigeration and foams (IPCC and TEAP, 2005) (see also Supp. Mat. Table S4). More recent numbers reported via the Montreal protocol indicate a similar level as ~100 percent of net global ODS consumption is comprised of hydrochlorofluorocarbons (HCFCs) (UNEP Ozone Secretariat, 2025), which are almost exclusively (97.68 percent) used for climate adaptation (see Supp. Mat. Table S6).

This first approximation needs to be refined as different ODSs have different ozone depletion potentials (ODPs). Global numbers for ODP-weighted ODS consumption unfortunately rarely distinguish between different end-uses. U.S. national statistics for 1985 showed 41.50 percent of ODP-weighted ODS production was related to climate adaptation (Statt, 1988). Globally, ODP-weighted ODS demand can be estimated at 76.22 percent in 2002 (see Supp. Mat. Table S5). More recent figures can be approximated based on the fact that ~100 percent of net global ODS consumption is comprised of 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 96.90 percent of 2023 ODP-weighted ODS consumption. Figure 4 illustrates these different approximations.

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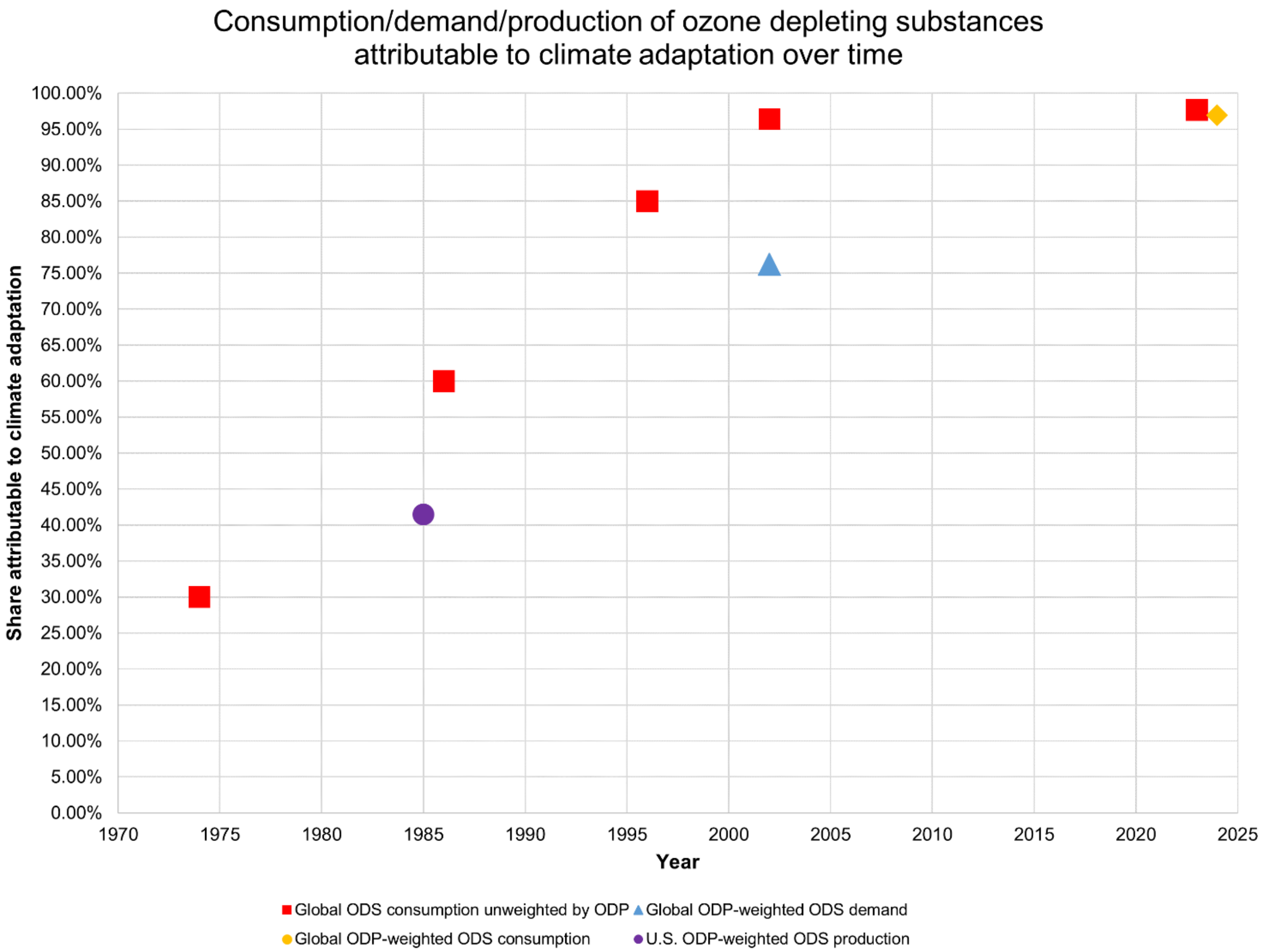

Figure 4: Consumption/demand/production of ozone depleting substances attributable to climate adaptation (refrigeration and insulation foams) over time. Consumption unweighted by ODP based on Daniel et al. (2007). U.S. production numbers based on (Statt, 1988). Demand of ODS weighted by ODP based on IPCC/TEAP (2005, p.408) and WMO (2022). For details see Suppl. Mat. Tables 4-6.

Given these lines of evidence, one could even venture to question whether the "ozone hole" would have occurred without climate adaptation in the first place. There are two caveats for this argument, though, and both are related to the success of the Montreal protocol. First, while climate adaptation probably contributed a majority of annual ODP-weighed ODS consumption after the 1990s, the largest surge in atmospheric concentrations of many ODS like CFC-11 already occurred in the 1970s and 1980s; e.g., CFC-11 concentrations reached a peak in the 1990s (Bullister and Warner, 2017). And second, as CFCs and most other ODSs including those related to climate adaptation have been regulated by the Montreal protocol, unregulated ODSs like N_2O have started exerting more and more influence on stratospheric ozone depletion processes (Ravishankara et al., 2009).

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However, this does not weaken the argument here. To the contrary: the success of the Montreal protocol including the Kigali amendment can demonstrate how respecting a safe operating space could look like for all forms of climate adaptation.

2.3. Human climate adaptation and the Planetary Boundary "freshwater change (blue water)"

The control variable of the Planetary Boundary "freshwater change" (blue water; i.e., surface and groundwater) is currently set as local streamflow deviations measured in percentage of disturbed global ice-free land compared to pre-industrial times (Porkka et al., 2024; Richardson et al., 2023). Calculating the impact of human climate adaptation on this Planetary Boundary would involve isolating the effect of adaptation-related streamflow deviations (e.g., water withdrawals for artificial precipitation (irrigation)) from all streamflow deviations. Unfortunately, such data at the streamflow-level of granularity and sufficient temporal resolution is currently not available for all relevant adaptation technologies. Therefore, a proxy will be used: annual human freshwater withdrawals. Freshwater withdrawals are not the only anthropogenic factor disturbing streamflow conditions (Best, 2019). For example, anthropogenic climate change has already emerged as one major stressor for streamflows globally (Asadieh and Krakauer, 2017; Gudmundsson et al., 2021). Land-use change also clearly affects streamflows (Levia et al., 2020). Yet freshwater withdrawals are still a proximate driver for many key factors shaping streamflow conditions. Moreover, in the early iterations of the Planetary Boundaries framework, the freshwater boundary was still defined in terms of global freshwater use (Rockström et al., 2009; Steffen et al., 2015a). In therefore stands to reason to utilise freshwater withdrawals as a provisional proxy until more comprehensive data becomes available. Whenever a direct influence of climate adaptation on streamflow conditions is evident, it is discussed qualitatively in the text.

2.3.1. Flow climate adaptation

Irrigation for agricultural production is one major factor influencing the control variables of several Planetary Boundaries (Campbell et al., 2017). It is also the most important pathway through which climate adaptation influences global freshwater withdrawals. Irrigations accounts for ~70 percent of global freshwater withdrawals (ground and surface water) (McDermid et al., 2023; Campbell et al., 2017). When not global freshwater withdrawals but freshwater consumption is considered, this figure rises up to 90 percent (McDermid et al., 2023). Both figures are surrounded by uncertainty (Puy et al., 2022, 2025). If it was not for inefficient irrigation technology, several hundred $km^3\ yr^{-1}$ could be saved by switching to e.g., drip systems (Jägermeyr et al., 2015).

Global water withdrawals for artificial snow production are uncertain. However, the estimate by François et al. (2023) for Europe at least indicates an order of magnitude that makes the contribution to overall global freshwater withdrawals probably negligible (~0.003 percent) even if other regions like North America were included in the estimate (see Supp. Mat.). Apart from irrigation, global freshwater use for the global energy system is also considerable with ~10 percent of annual freshwater

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withdrawals (IEA, 2024f). As artificial cooling corresponds to 1.80 percent of world total final energy consumption (IEA, 2024; IEA, 2024b), artificial cooling adds 0.20 percentage points to global annual freshwater withdrawals.

Desalination, currently equal to ~0.87 percent of annual freshwater withdrawals (Jones et al., 2019), involves water withdrawals but this water is seawater and not freshwater. As it might imply (future) avoided freshwater withdrawals, desalination is discussed here but neither subtracted from nor added to overall freshwater withdrawals. Relatedly, total global wastewater treated equalled at least 2.2×10^2 km³ in 2022 and some part of this might imply (future) avoided freshwater withdrawals (UN-Habitat and WHO, 2024). Yet for reasons of conceptual clarity (distinguishing water withdrawals from consumption), treated wastewater is not considered here in the attribution analysis.

Lastly, some forms of climate adaptation include groundwater management (Scanlon et al., 2023). Groundwater management influences the amount of freshwater withdrawals possible and is often only possible through appropriate freshwater withdrawal practices, which can in turn influence streamflow conditions (Chávez García Silva et al., 2024; Jasechko et al., 2024).

2.3.2. Boundary climate adaptation

Flow climate adaptation through irrigation is often enabled by boundary climate adaptation. In the case of irrigation, not only the direct effects of freshwater withdrawals disturb river flow regimes, but also the indirect effects of large-scale water infrastructure including artificial reservoirs, channels etc. (Biemans et al., 2011). Importantly, there can also be substantial indirect feedback effects from these reservoirs on the global hydrological cycle (Jaramillo and Destouni, 2015).

Annual embodied water in the global construction of buildings is uncertain, but can be approximated based on additions to global gross floor area and life-cycles studies to be ~3.00 percent of total annual freshwater withdrawals (see Supp. Mat.). Annual embodied water in clothes is also uncertain but can be approximated from Niinimäki et al. (2020) to be around 0.88 percent of total annual freshwater withdrawals (see Supp. Mat.). The estimate is uncertain given the authors mainly rely on industry sources.

The impact of water-sensitive urban and building design on the global scale is unclear but potentially positive as e.g., rainwater harvesting systems could replace some freshwater withdrawals and protect freshwater sources (Piemontese et al., 2020; Yuan et al., 2025). Similarly, the improvement of dikes and dams as well as proper flood management plans can safeguard freshwater resources from saltwater intrusion (Su et al., 2025) but the global impact on freshwater withdrawals is unclear.

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2.3.3. Behavioural climate adaptation

Freshwater withdrawals due to climate-related tourism, temporary relocation etc. are unclear (see discussion above). However, they could be potentially non-negligible (Becken, 2014).

2.3.4. Organic climate adaptation

Restoration and management of coastal wetlands as well the rehabilitation and restoration of rivers and floodplains do not affect freshwater withdrawals directly, but both forms of climate adaptation are important to safeguard freshwater sources (Convention on Wetlands, 2025). In addition to that, many organic forms of climate adaptation such as agro-forestry, conservation agriculture, and water-sensitive forest management could stabilise local hydrological cycles (Kassam et al., 2014; Rahman et al., 2023). This could also indirectly influence freshwater withdrawals; yet the global effect is currently still unclear.

Table 3 summarises these findings and shows climate adaptation is currently responsible for ~74.08 percent of annual total freshwater withdrawals. Almost all of this is due to irrigation. Figures 5 summarises these results visually. As recently shown, irrigation is hence also the most important factor affecting the blue water Planetary Boundary (Rockström et al., 2025).

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Functional layer of climate adaptation	Type of artificial climate niche (major group of ECVs modified)	Climate adaptation form	Share of most recent annual freshwater withdrawals	Source
Flow climate adaptation	Atmosphere	Freshwater withdrawals for power generation for artificial cooling	~0.20 %	Calculated based on (IEA, 2024; IEA, 2024b; IEA, 2024f)
		Freshwater withdrawals for artificial snow production	>0.003 %	Calculated based on (François et al., 2023) for Europe only (lower global bound). See Supp. Mat.
	Land / Ocean	Freshwater withdrawals for irrigation	~70.00 %	(Campbell et al., 2017; McDermid et al., 2023)
		Freshwater production through desalination	(~0.87 %)	Calculated based on (Jones et al., 2019). See Supp. Mat.
Boundary climate adaptation	Atmosphere	Embodied water in buildings	~3.00 %	Calculated based on (Dixit and Pradeep Kumar, 2024; UNEP, 2022). See Supp. Mat.
		Embodied water in clothing	~0.88 %	Calculated based on (Niinimäki et al., 2020). See Supp. Mat.
	Land / Ocean	Embodied emissions in blue infrastructure and coastal protection	+ ?	Unclear at the global scale
Behavioural climate adaptation	Atmosphere / Land / Ocean	Water withdrawals due to climate-related tourism, temporary relocation etc.	± ?	Unclear at global scale. Could be relevant (Becken, 2014)
Organic climate adaptation	Atmosphere / Land / Ocean	Various nature-based adaptation solutions	± ?	Unclear at the global scale but e.g., conservation agriculture and water-sensitive forest management can stabilise local hydrological cycles (Kassam et al., 2014; Rahman et al., 2023)
Total			**~74.08 %**	

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405 **Table 3: Functional layers of human climate adaptation, artificial climate niches, and estimated share of total global annual freshwater withdrawals from major corresponding adaptation options.**

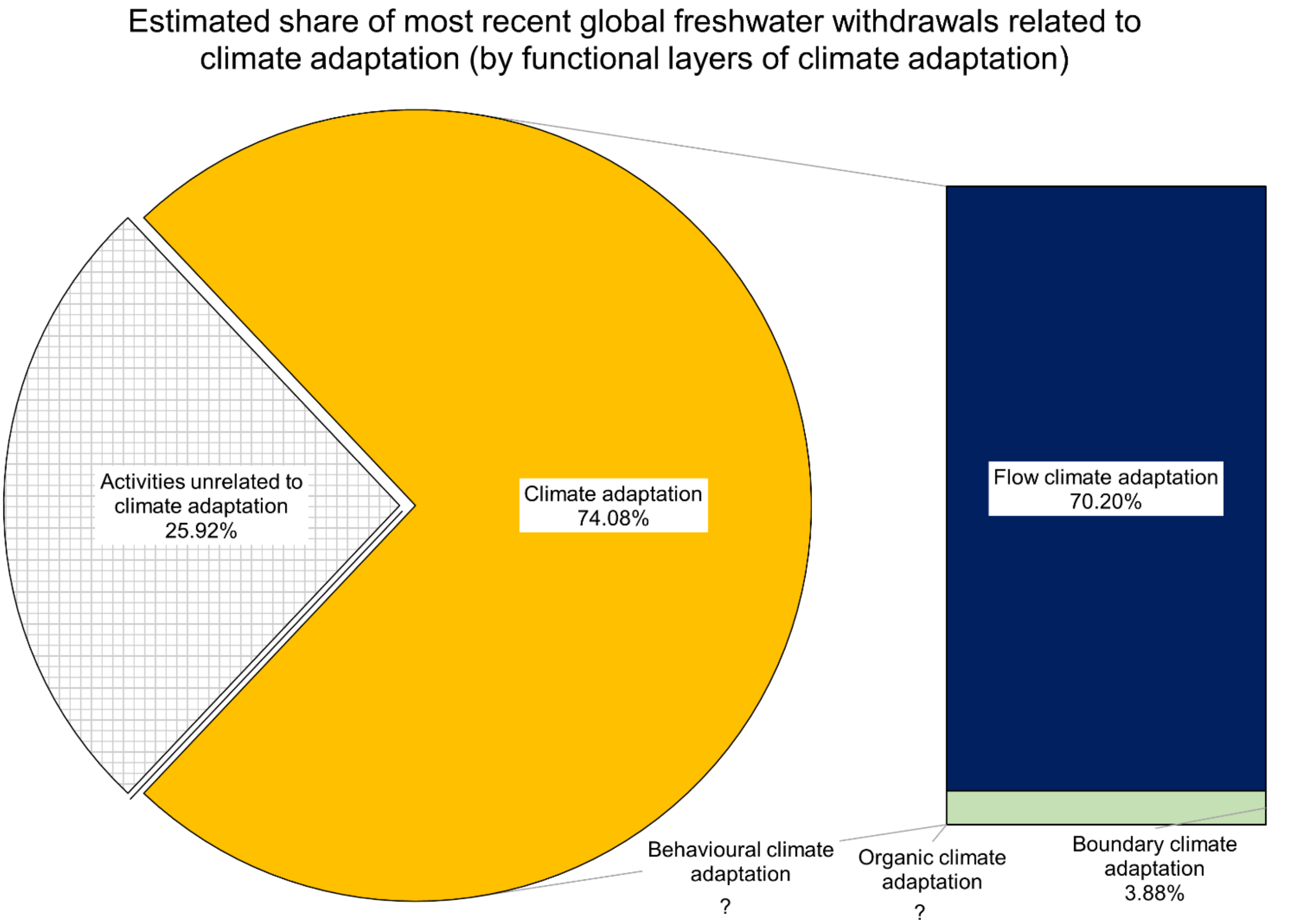

Figure 5: Estimated share of most recent global freshwater withdrawals related to climate adaptation. ~74.08 percent are estimated
410 **to be related to climate adaptation, ~25.92 percent are estimated to be unrelated. With ~70.20 percentage points, flow climate adaptation (mostly irrigation) contributes most strongly to adaptation-related freshwater withdrawals. The contribution of organic and behavioural climate adaptation is still unclear but likely to be much lower.**

3. The role of climate change in climate adaptation: decomposition

In Section 2, it was shown that the effects of climate adaptation on proxies for three major Planetary Boundaries could indeed
415 be substantial. More than a quarter of most recent annual GHG emissions and almost three quarters of human freshwater withdrawals as well as a large part of ODP-weighted ODS emissions are related to climate adaptation. These pressures on the

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Earth system are the result of economic activities undertaken with the purpose of establishing artificial climate niches. That is, essential climate variables such as air temperature or soil moisture are modified locally for human benefit and the ecological ramifications of this add-up to a global force. Yet so far, no distinction was made whether a) such climate adaptation was undertaken already in response to or anticipation of climate change or b) would also have occurred without climate change merely because of e.g., innovation, population or income growth. This distinction is not relevant if it is only to be investigated whether climate adaptation already affects the Earth system (which was the purpose of this paper). But it is highly relevant to investigate how these interactions could develop in a future driven by strong climate change. While the interactions found in this research here offer reasons for concern, it remains to be investigated whether they actually develop into self-amplifying feedbacks (as hypothesised in Fig. 2). While detailed counterfactual and econometric analysis is beyond the scope of this paper, at least an approximation shall be explored.

3.1. Climate change

Among all climate adaptation options assessed here, the effect of climate change on artificial cooling has been studied most. It is clear increasing cooling degree days affect the adoption of air conditioning (Colelli et al., 2022; Duan et al., 2023; Kennard et al., 2022). Climate change makes it necessary to cool more often and more intensely. Yet people in need for cooling will not be able to cool artificially if they cannot afford to pay for it (Pavanello et al., 2021). Energy consumption and GHG emissions related to artificial cooling have more than doubled since the year 2000 (Green Cooling Initiative, 2026; IEA, 2024c). Yet the International Energy Agency (IEA, 2018, 2024) estimates climate change explains only ~10 percent of predicted growth in energy demand for space cooling; growth in income, population, and urbanisation are far more important drivers. Similarly, a seminal paper found the effect of income growth on A/C adoption and usage to be at least three times larger than growth in cooling degree days (Davis and Gertler, 2015). Interestingly, a recent retrospective analysis by the authors found that changes in electricity prices and energy efficiency are as important as changes in income so that the estimated contribution of climate change shrinks to ~10-15 percent (Davis and Gertler, 2025). As an approximation, it is therefore conservatively assumed 10 percent of total GHG emissions related to artificial cooling are already driven by climate change (0.41 Gt CO_{2e} yr^{-1}). High geographical heterogeneity is likely.

Additionally, it seems likely that climate change also drives demand for irrigation (Rosa, 2022) and desalination (Jones et al., 2019). Here however, it is unclear which explanatory power changes in climate compared to population or income growth or changing consumption patterns already have. Accompanied by comparatively small increases in irrigated area, global freshwater withdrawals for irrigation have only marginally increased since the year 2000 (McDermid et al., 2023; Mehta et al., 2024; Siebert et al., 2015; Wada and Bierkens, 2014). Efficiency gains have likely outweighed increases in irrigation area (Jägermeyr et al., 2015). Recent regional studies indicate demographic and economic factors are very powerful determinants of irrigation water demand (Ou et al., 2023). In China, for instance, depending on the region, climate change could explain 10-

30 percent of changes in gross irrigation water demand (Fan et al., 2025). Operational desalination capacity has increased fivefold since the year 2000 but capacity is still concentrated in high income countries (Jones et al., 2019). It is unknown how strongly climate change affects desalination demand. Assuming climate change also explained 10 percent of irrigation and desalination demand, this would drive an estimated 0.06 Gt CO_{2e} yr^{-1}. This estimate is uncertain given limited literature and high geographical heterogeneity is likely.

Apart from this, at least a weak direct link also seems probable for buildings and climate change - especially in the case of insufficiently mitigated future climate change including e.g., large-scale sea level rise for centuries up to millennia. As illustrated by the 2011 Japan earthquake/tsunami (Tanikawa et al., 2014) and the 2004 hurricane Ivan (Symmes et al., 2020), the material loss in such large-scale catastrophes is likely to exceed millions of tons of matter. In general, structural reinforcements, replacements, and demolition become a larger issue due to flood, wildfire or storm damages and possibly also climate migration (Lenton et al., 2023; Merschroth et al., 2020). However, as of today there is little evidence overall global construction material flows are already affected by this in any substantial manner. Apart from these self-reinforcing links, there is only one probable self-attenuating link: artificial heating (Kennard et al., 2022). Despite regional evidence (Amonkar et al., 2023), here as well it remains unclear how strongly decreasing heating degree days already decrease heating demand globally. No clear relation between climate change and global clothing demand is evident.

In total, this approximation indicates adaptation to climate *change* could be responsible for currently ~0.47 Gt CO_{2e} yr^{-1}, that is 0.87 percent of total annual GHG emissions, and 3.40 percent of total climate adaptation-related annual GHG emissions, respectively. This approximation is uncertain but in line with the initial hypothesis that millennia of adaptation to largely fixed Holocene climates are still dominating current Earth system pressures. In other words, while ~25.56 percent of annual global GHG emissions is related to climate adaptation, the large majority of these emissions (96.60 percent) would probably also be emitted if there was no anthropogenic climate change. That is because in many regions the prevailing climate has apparently already initiated a sufficient need for adaptation which is now increasingly fulfilled through demographic, economic, and technological developments.

3.2. Stratospheric ozone depletion

As shown in Section 2.2, the recent ODP-weighted ODS consumption for the year 2023 is dominated by HCFCs, which in turn are almost exclusively used for climate adaptation. It was estimated that 96.90 percent of 2023 ODP-weighted ODS consumption was related to climate adaptation. If the estimate from the previous approximation for artificial cooling is applied, 9.66 percent of 2023 ODP-weighted ODS consumption was driven by climate change. As discussed above, this estimate is uncertain.

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3.3. Freshwater change

As explained above, it is unclear how strongly climate change is already affecting freshwater withdrawals for irrigation but it is likely other factors play a more dominant role. Moreover, there is no indication water withdrawals for building construction or clothes are already substantially driven by climate change. It is uncertain, how strong the effect of climate change on artificial snowmaking already is. Using a conservative estimate from above-cited studies, 10 percent of water withdrawals for irrigation and power generation for artificial cooling could be driven by climate change. According to this provisional approximation, climate change could be responsible for ~7.02 percent of current annual global freshwater withdrawals. High geographical heterogeneity is likely. This is an uncertain estimate, which ought to be investigated in more detail in future studies.

4. Discussion and conclusion

In the literature it is well-known local climate adaptation could cause global environmental impacts (e.g., Eriksen et al., 2011; Adger et al., 2009; Davis and Gertler, 2015). Some recent studies on this issue addressed some Earth system processes such as climate-energy-carbon feedbacks (Abajian et al., 2025; Colelli et al., 2022; Van Ruijven et al., 2019) or certain climate adaptation options such as irrigation (Lobell et al., 2008; Rosa, 2022). Yet to the best of our knowledge, there is currently no holistic assessment covering all relevant Earth system processes and all relevant climate adaptation options. This substantial research gap needs to be addressed as current climate change projections imply an unprecedented global acceleration of climate adaptation if just to alleviate the most severe, unavoidable impacts. It is crucial to address these needs for climate adaptation by means which do not threaten a further transgression of the Planetary Boundaries. Here, via literature screening, a subset of direct and potentially substantial climate adaptation-Earth system-interactions ranging across all control variables of all Planetary Boundaries was identified. In a second step, an attribution analysis for the subset of most relevant interactions was conducted by measuring the current influence of climate adaptation on common proxies for the respective Planetary Boundaries. This enabled the estimation of a baseline for today’s pressures on the Earth system generated by climate adaptation. Lastly, in an approximate decomposition, the contribution of climate change to such current pressures was estimated. That is, it was estimated which part of climate adaptation-related pressures only occurred due to climate change in contrast to other enabling factors such as population or income growth.

Artificial temperature niches occupy only ~0.1-0.2 percent of land, artificial precipitation niches ~3 percent of land, and artificial flood protection niches ~0.01 percent of ocean area (Ott et al., in review). Yet indirect climate adaptation-Earth system-interactions are extremely disproportional to scale. Aggregated across artificial climate niches, human climate adaptation currently contributes ~25.56 percent of annual GHG emissions, ~74.08 percent of human freshwater withdrawals, and a large part of emissions of ozone depleting substances. As discussed in Section 2, this is a conservative, lower-boundary estimate as the impacts of some forms of climate adaptation such as embodied water or carbon in coastal protection

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infrastructure is not yet clear at the global level but very likely larger than zero. It was also shown that the majority of these impacts is connected to certain functional mechanisms of climate adaptation, primarily flow but also boundary climate adaptation. Overall, this clearly demonstrates there are indeed substantial climate adaptation-Earth system-interaction when measured via proxies for the Planetary Boundaries. Moreover, this also demonstrates the utility of differentiating different forms of climate adaptation based on their socio-metabolic profiles. As discussed in Section 3, all these interactions are estimated to mainly still result from better means for adaptation in general (driven by income, technology, and population growth) and not yet from climate change. This preliminary analysis provides reasons for concern that self-reinforcing feedbacks of human climate adaptation on the Planetary Boundaries could accelerate the depletion of the stability and resilience of the Earth system. But it also clarifies how large the Earth system pressures resulting from adaptation to mostly fixed climates still are. Figure 6 summarises these findings.

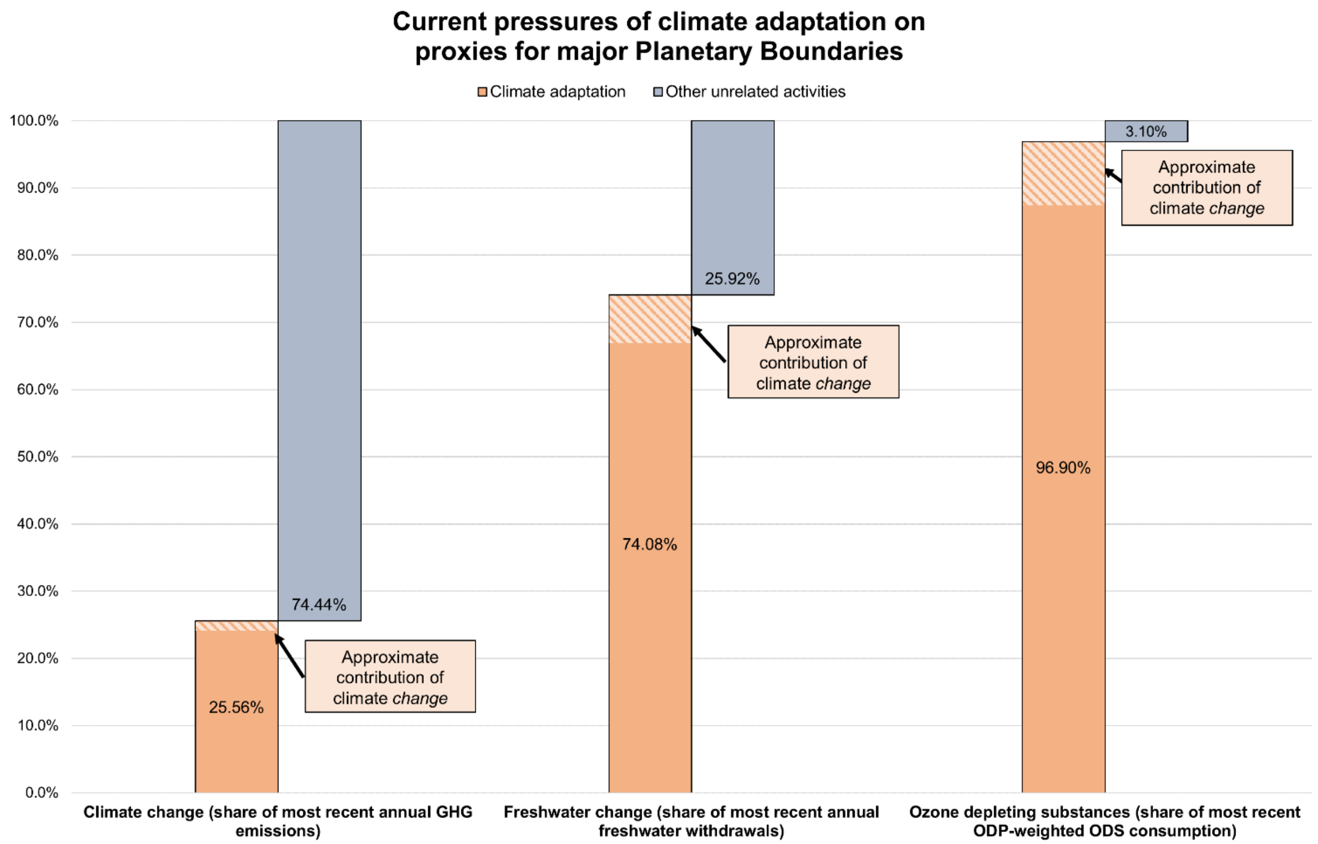

Figure 6: Current pressures of climate adaptation on proxies for major Planetary Boundaries. For each of the proxies, the share related to climate adaptation is shown in contrast to the share unrelated to climate adaptation. Approximations for the contribution of climate change to climate adaptation-related pressures is shown next to the bars. For all proxies, it is estimated climate change so far contributes only a minority of climate adaptation-related pressures.

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This study is of course not the first to highlight that current levels of greenhouse gas emissions, freshwater withdrawals, and ozone depletion constitute problems of global concern. But to the best of our knowledge, it is among the first publications to systematically show how strongly these concerns are also driven by human climate adaptation. Therefore, climate adaptation can and does diminish the stability and resilience of the Earth system already today. This shows the importance of understanding and governing the consequences of adaptation to anthropogenic climate change. Moreover, this study helps establish a baseline for Earth system pressures related to climate adaptation, which helps evaluate recent studies on future projections for climate-adaptation-Earth system-feedbacks. For instance, a recent study (Abajian et al., 2025) surprisingly found climate change might result in substantial cumulative GHG reductions until the end of the century as reduced heating-related emissions outweigh growing cooling-related emissions. Our study casts doubt on these findings given already today cooling-related emissions are basically at the same level as heating-related emissions (4.09 vs. 4.16 Gt CO_{2e}) if all GHGs and not just CO_2 are considered. It is very likely cooling-related GHG emissions will increase further (UNEP, 2023), while it is physically unlikely heating-related emissions will become negative.

Still, there are some limitations in our study. Here, for exploratory purposes, discrete data points for proxies were used to account for the control variables of a selection of relevant Planetary Boundaries. While this is sufficient for the exploratory stage, directly measuring the impact of climate adaptation on these control variables could be worthwhile. This would involve additional data not available at the date of this publication and explicit modelling of Earth system processes. For example, as discussed above, for the Planetary Boundary "stratospheric ozone depletion" this would involve a full time series of cumulative ODP-weighted ODS emissions based on detailed end-uses, which would then be processed in a suitable atmospheric model with a high-resolution chemistry module in order to simulate global stratospheric ozone dynamics. While it seems unlikely more data fundamentally changes the estimations of climate adaptation-Earth system-interactions as described here, more data could reveal existing nuances within these interactions. Additionally, many of the estimates here have unknown uncertainty bounds. Specifying these bounds through explicit modelling could be worthwhile. Importantly, the discrete proxy data points used here only represent single years but pressure on the Planetary Boundaries is a result of cumulative stressors extending over decades to centuries. This is most evident for stratospheric ozone depletion. While climate adaptation might drive 96.90 percent of 2023 ODP-weighted ODS consumption, the overwhelming majority of ODS consumption occurred decades earlier. Moreover, it might also be useful to extend the present analysis by explicitly attributing not just direct but also indirect interactions of climate adaptation with relevant Planetary Boundaries. Similarly, the investigation of additional types of artificial climate niches (e.g., fluvial flood protection), forms of adaptation or spatially-explicit data could be enriching. While the analysis undertaken here is holistic in its nature, there are of course limitations based on limited literature at the global level and limited modelling capacity.

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This research paper aimed to investigate whether there are substantial climate adaptation-Earth system-interactions when measured via common proxies for the Planetary Boundaries. Now that substantial interactions have been identified, they ought to be analysed in much more detail. In future research, it will become necessary to disentangle the drivers of these feedbacks explicitly and in more detail using e.g., process-based World-Earth models (Donges et al., 2020). Further, for policy, it seems advisable to investigate how to best decouple human climate adaptation from destabilising Earth system feedbacks. Equally important, there is a need to foster these few restorative, stabilising climate adaptation-Earth system-feedbacks such as urban forests (Teo et al., 2021) and other nature-based solutions (Chmura et al., 2003; Morris et al., 2018; Song et al., 2023). Right now, climate adaptation, which is crucial to protect human societies from the inevitable consequences of climate change, in itself is causing additional climate change. This presents an unsustainable positive feedback loop, which can undermine Earth system functioning, stability, and resilience. Fortunately, the decarbonisation of the global building stock as well as of global heating and cooling system is already relatively high on the policy agenda (UNEP, 2023, 2025b). But such decoupling seems to be less a priority in e.g., adaptation to coastal flooding (Nieuwkamer et al., 2022). Given these results, there is an urgent need to find ways to accelerate global climate adaptation while respecting the safe operating space of the Planetary Boundaries.

5. Data availability

All data necessary to validate the findings is included in the manuscript, the supplementary material or the cited references.

6. Competing interests

Jonathan F. Donges is a member of the editorial board of Earth System Dynamics. The authors declared no other potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

7. Author contributions

Bastian Ott: conceptualisation, writing of the original draft, investigation, formal analysis, visualisation. Jonathan F. Donges and Johan Rockström: writing (review & editing) and supervision.

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