Respecting the boundaries: balancing climate adaptation and Earth system resilience

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Abstract

Humans have always adapted to their local climate. Today, human activities are also unintentionally changing the global climate. This will require major adaptations, which cannot replace and must not derail efforts to stop climate change. Yet measures such as cooling buildings or irrigating crops can themselves increase environmental pressures on the Earth system. Using the Planetary Boundaries framework, we combine evidence to estimate the current pressures associated with adaptation to i) Holocene-like climates and ii) anthropogenic climate change. Our first-order estimates indicate that climate adaptation currently contributes ~25.6 percent of annual greenhouse gas emissions and ~74.1 percent of annual human freshwater withdrawals. Climate adaptation even affects the stratosphere: cooling technologies have considerably contributed to ozone depletion. This confirms that climate adaptation currently exerts substantial pressures on the Earth system. Only a minority of these pressures are likely to be driven by anthropogenic climate change; most still result from economic, technological, and population growth and might also have occurred without climate change. But as climate change dramatically increases the need for adaptation, these findings underscore the importance of scaling adaptation in ways that protect people without further destabilising the Earth system.

Keywords

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

Introduction

Humans have always adapted to their local climate and natural climatic changes (deMenocal, 2011). However, the necessary pace and scale of adaptation to anthropogenic climate change is unparalleled. Even within the limits of the Paris Agreement, adaptation to unprecedented climates is unavoidable (IPCC, 2022a; 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 (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?

The literature has long debated the need for balancing the *economic* dimension of climate change with the costs and benefits of adaptation and mitigation (e.g., Nordhaus, 1991; Stern, 2007). Here we would like to introduce a different, *biogeophysical* dimension, namely the need to also balance the necessity of climate adaptation with the biogeophysical limits of the Earth system. The purpose of this study is to establish a baseline of *current* Earth system pressures generated by *all* forms of climate adaptation – that is adaptation to local, Holocene-like climates as well as adaptation to anthropogenic climate change. This broad, Earth system-based 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 through e.g., irrigation, heating or buildings comprises thousands of 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. In line with IPCC terminology, the term climate adaptation is used here in an overarching sense describing the "process of adjustment to [both] actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities" (IPCC, 2022c, p. 5). The subset of climate adaptation which would not have been necessary without anthropogenic climate change is explicitly termed climate change adaptation in order to avoid possible misinterpretations.

The case of fossil fuels shows how initial, local environmental effects have scaled up to the planetary level as combustion technologies spread globally (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 could be expected that the planetary consequences of climate adaptation emerged in a similar manner. Yet given that humans adapt to climate change almost exclusively locally (Berrang-Ford et al., 2021), the systematic assessment of potential climate adaptation-Earth system interactions is still in its infancy. Several authors cautioned 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 (Andrijevic et al., 2023; Colelli and Cian, 2020; Holman et al., 2019; Van Maanen et al., 2023). 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; Rosa, 2022). Several others focused on greenhouse gas (GHG) feedbacks related to energy-intensive forms of climate adaptation such as air conditioning, yet the results are partially contradictory. Some authors project strongly increasing energy demand and GHG 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 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., 2026) laid the groundwork for this by establishing a purely Earth system-based definition of climate adaptation. From this perspective, climate adaptation almost always materialises in what the authors have termed *artificial climate niches*: "spatially-confined niche in which climate adaptation manifests as the significant, temporary, and intentional modification of essential climate variables by humans and for human benefit (ibid., p. 12). 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) (Global Climate Observing System, 2024) modified in each case. Those artificial climate niches are established through four different functional mechanisms of adaptation: *organic, behavioural, boundary,* and *flow climate adaptation*; detailed definitions and major examples are recapitulated below:

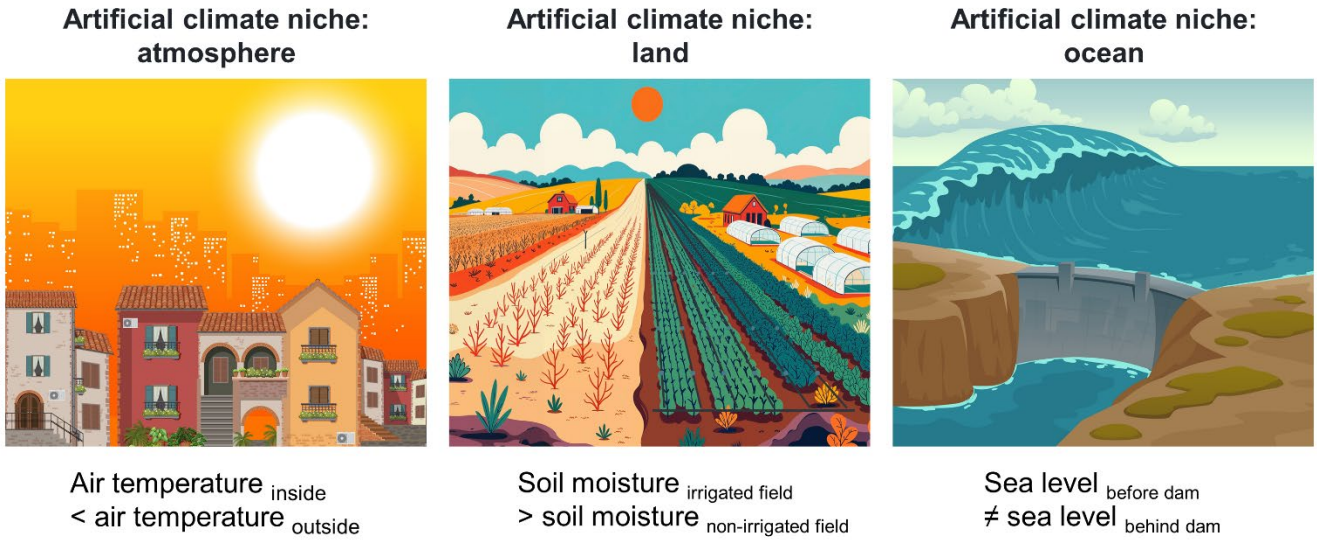

Figure 1: Examples of three artificial climate niches and the respective essential climate variables (ECVs) modified in each case. For details on the concept see Ott et al. (2026).

Key concepts and definitions

- **Climate adaptation**: "process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities" (IPCC, 2022c, p. 5). The subset of climate adaptation which would not have been necessary without anthropogenic climate change is explicitly termed "climate change adaptation."
- **Artificial climate niche**: "spatially-confined niche in which climate adaptation manifests as the significant, temporary, and intentional modification of essential climate variables by humans and for human benefit. Within these niches, climate variables cannot be predicted by standard meteorological models (that exclude human influence) alone." (Ott et al., 2026, p. 12)
- **Flow climate adaptation**: "Initiation of new flows of energy or matter in order to regulate a certain climate" (ibid.). Examples include artificial cooling, 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" (ibid.). Examples include buildings, improved insulation or seawalls
- **Behavioural climate adaptation**: "Temporary or permanent relocation to other existing natural/artificial climate niches" (ibid.). Examples include weather-sensitive behaviour or retreat from high-risk areas.
- **Organic climate adaptation**: "Self-sustaining systems that organically regulate a certain climate through their own anatomy/metabolism" (ibid.). Examples include afforestation, agro-forestry or coastal wetland restoration.

Defining climate adaptation in biophysical terms makes it possible to quantify its effects using established frameworks from Earth system sciences. One particularly relevant framework for such an assessment are the Planetary Boundaries, which are

proven to be well-suited to capture a whole range of relevant anthropogenic influences on the Earth system on a common level of resolution (Rockström et al., 2009; Steffen et al., 2015a; Richardson et al., 2023; PBScience, 2025). The Planetary Boundaries (PBs) represent thresholds for "nine Earth system processes essential for maintaining global stability, resilience and life-support functions." (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 this framework. We therefore investigate whether human climate adaptation contributes to the transgression of the Planetary Boundaries. 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.

Outline and methods

In the first part of this paper (Section 1), 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 69 common climate adaptation options on proxies for the respective control variables of the Planetary Boundaries 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., 2026), the attribution results are also decomposed into functional mechanisms of climate adaptation and artificial climate niches. 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).

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

First, >17,000 research articles in the Scopus literature database were screened 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, we searched for interactions 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). Additionally, one needs to consider that the way climate adaptation affects the Planetary Boundaries could also be amplified or attenuated by interactions across different Planetary Boundaries. For instance, GHG emissions related to climate adaptation might exacerbate climate change. However, climate change also drives loss in biosphere integrity and land system change, which in turn further contribute to climate change. Such interactions across Planetary Boundaries are included in the analysis here if evaluated as being of "high" relative importance based on the most recent review of the Planetary Boundaries (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. Table 1 and Fig. 2 exhibit the results of this analysis.

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 GHG emissions from artificial **cooling**	**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 (ODSs) from artificial **cooling 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 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 (PBScience, 2025).

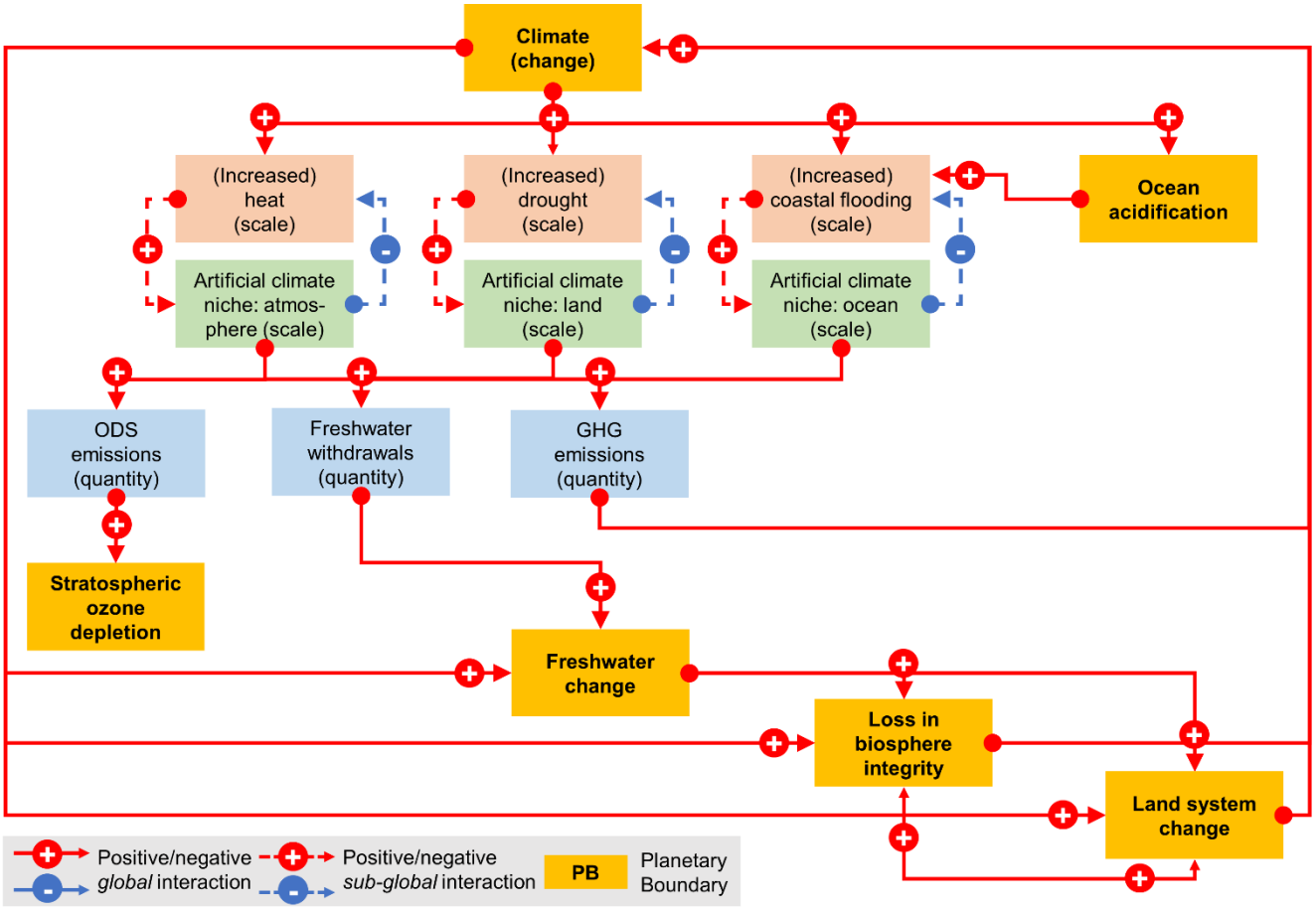

Figure 2: Plausible interactions of climate adaptation with Planetary Boundaries based on literature review. Positive (amplifying) interactions in red and negative (dampening) interactions in blue. Dashed lines indicate sub-global instead of global interactions. Note: not all interactions with all Planetary Boundaries shown for reasons of conceptual clarity. Interactions between Planetary Boundaries included if assessed as being of "high" relative importance in the most recent Planetary Health Check (PBScience, 2025). Interactions between climate change and artificial climate niches based on Ott et al. (2026). 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. As identified here, most planetary-scale feedbacks of human climate adaptation on the Earth system appear 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, 2025b). 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

of some interactions and hence feedbacks is still unclear. Additionally, no interactions between Planetary Boundaries 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 (Ott et al., 2026), this attribution analysis here comprises two different samples of adaptation options. First, adaptation options to anthropogenic climate change are sampled from the Climate-ADAPT database (Climate-ADAPT, 2026). This database, featured in the UNFCCC Adaptation Knowledge Portal, is one of the most comprehensive available and is regularly used by policymakers as well as researchers. Additionally, adaptation to Holocene-like climates is captured from the recent literature on the technosphere component "ambient context" (Galbraith et al., 2025). The full list of these 69 different climate adaptation options can be found in Suppl. Mat. Table S2. If an adaptation option results in an artificial climate niche, that option is fully accounted for as climate adaptation even if it also fulfils other secondary functions (e.g., buildings, clothing or irrigation). For a detailed discussion on this Earth system-based classification logic, please see Ott et al., (2026). For each of the selected Planetary Boundaries, the impact of different forms of climate adaptation on the respective proxies for the control variables is assessed. These impacts are further decomposed into functional mechanisms of adaptation and artificial climate niches. On a cautious note, relevant literature could not be found for all forms of climate adaptation.

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 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 4.1 Gt CO_{2e} in 2022 (UNEP, 2023). Heating-related GHG emissions were estimated at 4.2 Gt CO_{2e} in 2022 (IEA, 2024c). 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 0.2 Gt CO_{2e} (Qin et al., 2024).

GHG emissions related to global desalination can be approximated to be ~0.4 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).

2.1.2. Boundary climate adaptation

Annual embodied GHG emissions related to the construction and refurbishment of buildings were estimated at 2.2 Gt CO_{2e} in 2019 (IPCC, 2022b, p. 963). Apparently little has changed since then (UNEP, 2025c) but some integrated assessment models calculate with even higher numbers (Zhong et al., 2021). Clothing-related GHG emissions were estimated at 2.9 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, for example, 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 to date 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., 2026) 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, salt marshes and coastal wetlands protect coasts organically against 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 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): 0.1 Gt CO_{2e} yr^{-1}. Table 2 shows an overview of the four functional mechanisms 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 an initial estimate as the GHG emissions of many relevant categories cannot yet be reliably estimated.

Functional mechanisms 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	4.1	Based on (UNEP, 2023)
		Artificial heating	4.2	Based on (IEA, 2024c)
	Atmosphere / Land	Irrigation	0.2	Based on (Qin et al., 2024)
	Land / Ocean	Desalination	~0.4	Calculated based on (IEA, 2024b) and 2023 grid factors from (Ember Climate, 2024).
Boundary climate adaptation	Atmosphere	Buildings (embodied emissions)	2.2	Based on (IPCC, 2022b, p. 963)
		Clothing (embodied emissions)	2.9	Based on (Niinimäki et al., 2020)
	Land / Ocean	Blue infrastructure (embodied emissions)	+ ?	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	- 0.1	Inferred from (Teo et al., 2021).
	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			**~13.8 Gt CO_{2e}**	

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

In summary, annual GHG emissions related to human climate adaptation currently equal approximately 13.8 Gt CO_{2e}. This implies ~25.6 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 mechanisms 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 initial evidence of the substantially different impact different functional mechanisms of climate adaptation can have on the Earth system.

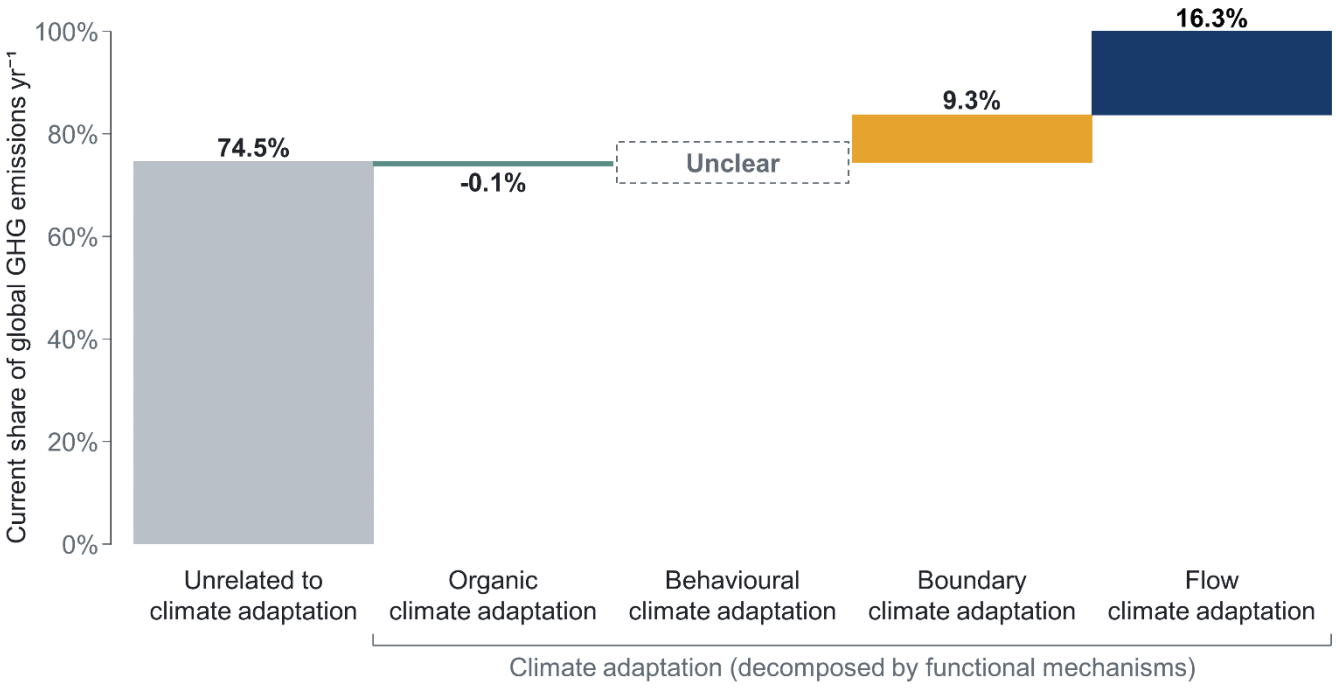

Figure 3: Estimated share of most recent annual global GHG emissions related to current climate adaptation. The contribution of climate adaptation is decomposed into different functional mechanisms of climate adaptation. Climate adaptation includes both adaptation to Holocene-like climates and anthropogenic climate change (the contribution of each is discussed in section 3.1.). Approximately 25.6 percent of most recent annual GHG emissions are related to climate adaptation. Were it not for organic climate adaptation, a small carbon sink, this share would be 0.1 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 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 comprised 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 composed of climate adaptation technologies like insulation 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, 96.4 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 for the year 2023 approximated from Montreal Protocol reporting indicate a similar level of ~97.7 percent (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 41.5 percent of ODP-weighted ODS production was related to climate adaptation (Statt, 1988). Globally, ODP-weighted ODS demand related to climate adaptation can be estimated at 76.2 percent in 2002 (see Supp. Mat.

Table S5). Most recently, 2023 ODP-weighted ODS consumption related to climate adaptation can be estimated at 96.9 (see Supp. Mat. Table S6). Figure 4 illustrates these different estimates.

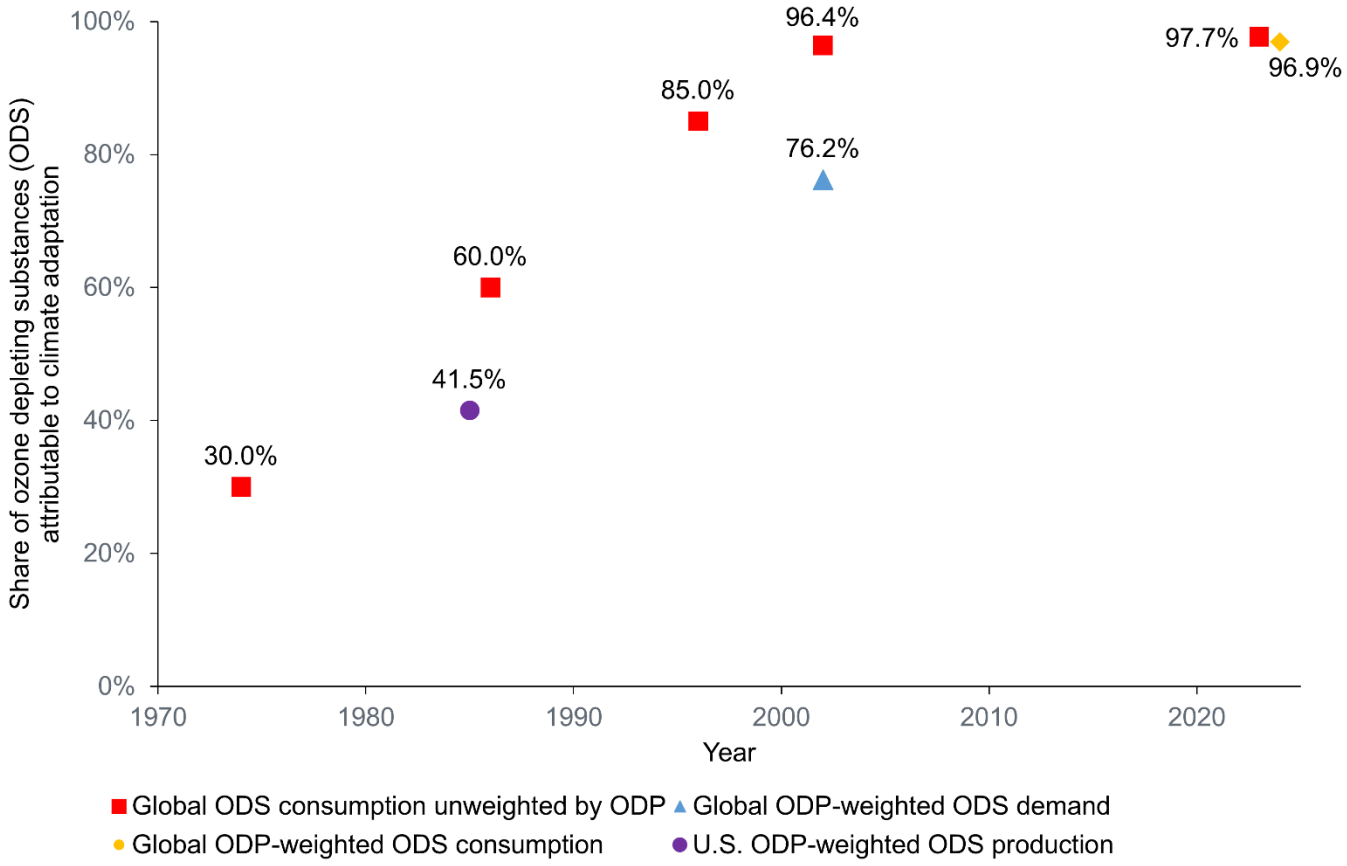

Figure 4: Consumption/demand/production of ozone depleting substances (ODS) attributable to climate adaptation (cooling and insulation foams) over time. Climate adaptation includes both adaptation to Holocene-like climates and anthropogenic climate change (the contribution of each is discussed in section 3.2.). Consumption unweighted by ozone depletion potential (ODP) based on Daniel et al. (2007). U.S. production numbers based on Statt (1988). Demand of ODS weighted by ODP based on IPCC and TEAP (2005, p. 408) and WMO (2022). For further 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-weighted ODS consumption after the 1990s, the largest surge in atmospheric concentrations of many ODSs 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).

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 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). It 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 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. Irrigation 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 to 90 percent (McDermid et al., 2023). Both figures are subject to 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).

Apart from irrigation, freshwater use for the global energy system is also considerable with ~10 percent of annual freshwater withdrawals (IEA, 2023a). As artificial cooling corresponds to 1.8 percent of world total final energy consumption (IEA, 2023b, 2024d), artificial cooling adds 0.2 percentage points to global annual freshwater withdrawals.

Desalination, currently equivalent to ~0.9 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 volume of freshwater that can be withdrawn 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 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 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 0.9 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.

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 as 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, 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.

Functional mechanisms 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	Artificial cooling (freshwater withdrawals for power generation)	~0.2 %	Calculated based on (IEA, 2023b, a, 2024d)
	Land / Ocean	Irrigation (freshwater withdrawals)	~70.0 %	(Campbell et al., 2017; McDermid et al., 2023)
Boundary climate adaptation	Atmosphere	Buildings (embodied water)	~3.0 %	Calculated based on (Dixit and Pradeep Kumar, 2024; UNEP, 2022). See Supp. Mat.
		Clothing (embodied water)	~0.9 %	Calculated based on (Niinimäki et al., 2020). See Supp. Mat.
	Land / Ocean	Blue infrastructure (embodied water)	+ ?	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			**~74.1 %**	

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

Table 3 summarises these findings and shows that climate adaptation is currently responsible for ~74.1 percent of annual total freshwater withdrawals. Almost all of this is due to irrigation. Figure 5 summarises these results visually. As recently shown, irrigation is hence also one of the most important factors affecting the blue water Planetary Boundary (Rockström et al., 2025; Virkki et al., 2026).

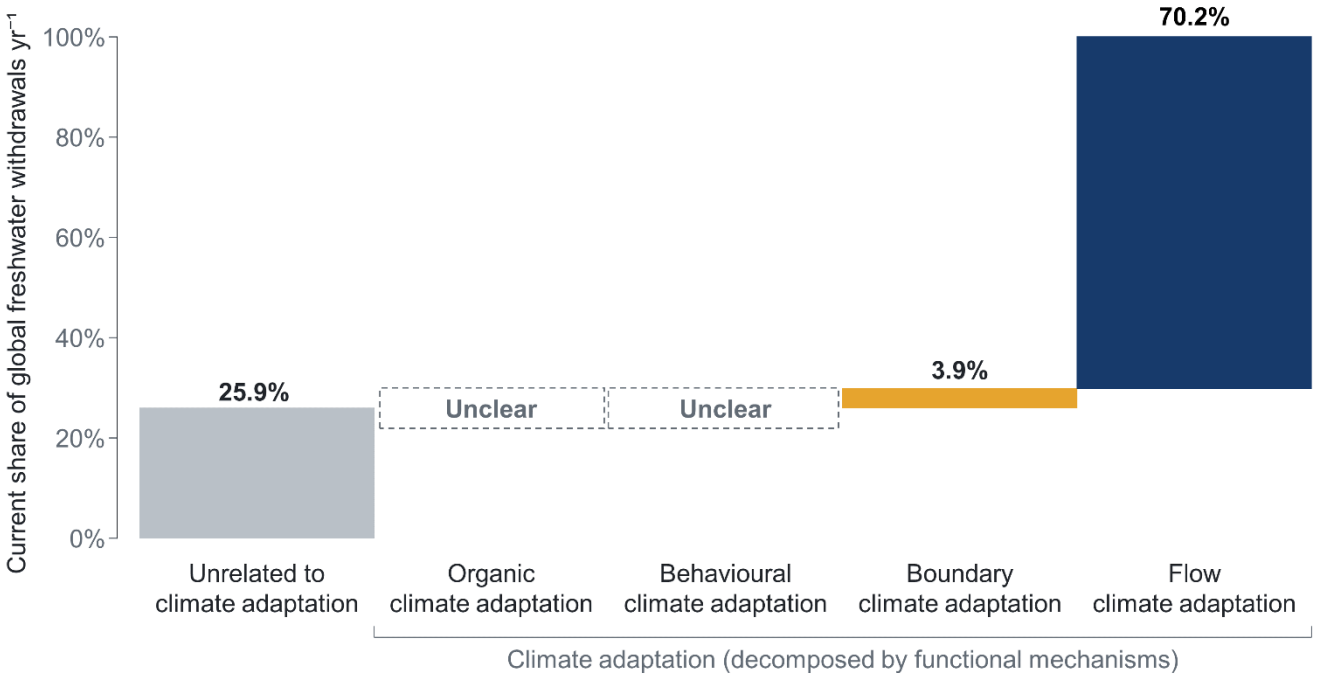

Figure 5: Estimated share of most recent global freshwater withdrawals related to climate adaptation. Climate adaptation includes both adaptation to Holocene-like climates and anthropogenic climate change (the contribution of each is discussed in section 3.3.). Climate adaptation is estimated to account for ~74.1 percent of freshwater withdrawals, while ~25.9 percent is estimated to be unrelated. With ~70.2 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.

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 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 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 such climate adaptation was undertaken a) already in response to or anticipation of climate change or b) could also have occurred without climate change merely because of e.g., technological 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 through proxies for the Planetary Boundaries. But it is highly relevant if we want to investigate *how* these interactions could develop in a future driven by strong climate change. While the interactions identified in this study 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 a first-order 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 that 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, 2024; IEA, 2024a). Yet the International Energy Agency (IEA, 2018, 2024d) estimates that climate change explains only ~10 percent of growth in energy demand for space cooling; growth in income, population, and urbanisation are far more important drivers. According to UNEP (2025b), only 12.5 percent of the predicted increase in cooling-related GHG emissions is due to extreme heat. Those effect sizes are supported by the seminal study of David and Gertler (2015) and especially their recent retrospective analysis (2025). As an approximation, it is therefore conservatively assumed that 10 percent of total GHG emissions related to artificial cooling could be driven by climate change (0.4 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 that demographic and economic factors are powerful determinants of irrigation water demand (Ou et al., 2023). Large spatial heterogeneity and substantial uncertainty is likely (Citrini et al., 2025). Globally, irrigation water demand is estimated to increase by ~10 percent across RCPs until 2050 due to climate change (Wada et al., 2013). Operational desalination capacity has increased fivefold since the year 2000 but capacity is still concentrated in high-income countries (Jones et al., 2019). Despite uncertainty and depending on model assumptions and scenarios, a ~10 percent increase in desalination water demand due to climate change could be a reasonable estimate (Rosa et

al., 2026). Assuming climate change also explained 10 percent of irrigation and desalination demand, this would drive an estimated 0.1 Gt CO_{2e} yr^{-1}.

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 that 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 first-order approximation indicates adaptation to climate *change* could be responsible for currently ~0.5 Gt CO_{2e} yr^{-1}, that is 0.9 percent of total annual GHG emissions, and 3.4 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 ~25.6 percent of annual global GHG emissions is related to climate adaptation, the large majority of these emissions (96.6 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, it was estimated that 96.9 percent of 2023 ODP-weighted ODS consumption was related to climate adaptation. If climate change explains ~10 percent of artificial cooling demand, it would drive an estimated 9.7 percent of 2023 ODP-weighted ODS consumption . As discussed above, this estimate is subject to uncertainty.

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 that water withdrawals for building construction or clothes are already substantially driven by climate change. 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 ~7.0 percent of current annual global freshwater withdrawals. High geographical heterogeneity is likely. This is an uncertain first-order estimate, which ought to be investigated in more detail in future studies.

4. Discussion and conclusion

In the literature it is well-known that 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 only to alleviate the most severe, unavoidable impacts. It is crucial to address those needs for climate adaptation by means which do not threaten a further transgression of the Planetary Boundaries. Here, through a literature screening, we identified a subset of direct and potentially substantial climate adaptation-Earth system interactions ranging across all control variables of all Planetary Boundaries. 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 a first-order 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 percent of land, artificial precipitation niches ~2.5 percent of land, and artificial sea level niches ~0.6 percent of ocean area (Ott et al., 2026). Climate adaptation only modifies relatively small areas directly. Yet the indirect environmental effects of that adaptation are disproportionally large. Aggregated globally, human climate adaptation currently contributes ~25.6 percent of annual GHG emissions, ~74.1 percent of human freshwater withdrawals, and a large part of emissions of ozone depleting substances. Overall, this clearly shows that there are indeed substantial effects of climate adaptation on the Earth system when measured through proxies for the Planetary Boundaries. It was also shown that the majority of these impacts are associated with certain functional mechanisms of climate adaptation, primarily flow but also boundary climate adaptation. This illustrates the utility of differentiating different forms of climate adaptation based on their biophysical mechanisms. As discussed in Section 2, this is a first-order estimate as the impacts of some forms of climate adaptation such as embodied water or carbon in coastal protection infrastructure are not yet clear at the global level but likely larger than zero. On the other side, especially the effects of organic and behavioural climate adaptation are difficult to quantify,

which inhibits attribution. 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 analysis provides reasons for concern that self-reinforcing feedbacks from climate adaptation could further destabilise 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.

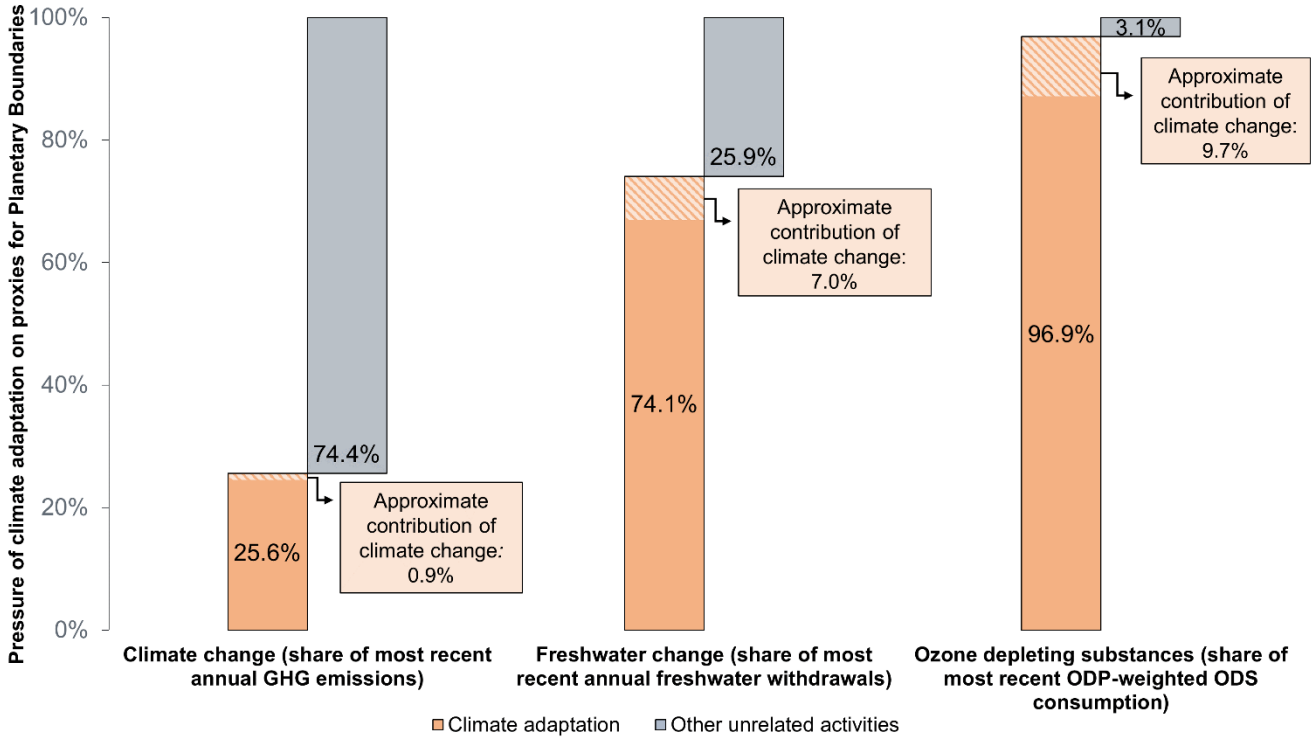

Figure 6: Current pressures of climate adaptation on proxies for major Planetary Boundaries. For each of the proxies, the share related to climate adaptation is shown in contrast to the share unrelated to climate adaptation. Approximations for the contribution of climate change to climate adaptation-related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

This study is 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. Our results indicate that climate adaptation already contributes substantially to current Earth system pressures. 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) counterintuitively argued climate change might result in substantial future cumulative CO_2 *reductions* as reduced heating-related emissions were found to outweigh

growing cooling-related emissions. As our focus was on current emissions, we have not conducted process-detailed modelling of future emissions. Yet our analysis of current emissions casts doubt on these findings. Abajian et al. excluded non-CO_2 GHGs from their analysis. As our analysis shows, this is likely a critical limitation given the substantial contribution of HFCs and HCFCs to current cooling-related GHG emissions (UNEP, 2025b; Lickley et al., 2020; Velders et al., 2007, 2022).

Still, there are some limitations in our study. Here, for exploratory purposes, current Earth system pressures were estimated based on proxy indicators for selected Planetary Boundaries. While this is sufficient for the exploratory stage, directly measuring the impact of climate adaptation on the boundary 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 ozone depletion, for example, this would require a full time series of historical end-use-specific emissions data coupled to a suitable atmospheric chemistry model. While it seems unlikely that additional data would fundamentally change our core findings, further nuances might be discovered. Moreover, many of the estimates here have unknown uncertainty bounds, which inhibits uncertainty propagation. Specifying these bounds through explicit modelling could be worthwhile. Importantly, the most recent 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 96.9 percent of 2023 ODP-weighted ODS consumption, the overwhelming majority of ODS consumption occurred decades earlier. Lastly, it might also be useful to investigate additional forms of adaptation or incorporate spatially explicit data. 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.

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 such 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 coupled human-Earth system models (Donges et al., 2020). Further, from a policy perspective, 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, is itself causing additional climate change. This presents an unsustainable positive feedback loop which could undermine Earth system functioning, stability, and resilience. Fortunately, the decarbonisation of the global building stock as well as of global heating and cooling systems is already relatively high on the policy agenda (UNEP, 2025c, b). But such decoupling seems to be less a priority in, for example, 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 are 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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10. References

Abajian, A. C., Carleton, T., Meng, K. C., and Deschênes, O.: Quantifying the global climate feedback from energy-based adaptation, Nat. Commun., 16, 3928, https://doi.org/10.1038/s41467-025-59201-7, 2025.

Adger, W. N., Eakin, H., and Winkels, A.: Nested and teleconnected vulnerabilities to environmental change, Front. Ecol. Environ., 7, 150–157, https://doi.org/10.1890/070148, 2009.

Amonkar, Y., Doss-Gollin, J., Farnham, D. J., Modi, V., and Lall, U.: Differential effects of climate change on average and peak demand for heating and cooling across the contiguous USA, Commun. Earth Environ., 4, 402, https://doi.org/10.1038/s43247-023-01048-1, 2023.

Andrijevic, M., Schleussner, C.-F., Crespo Cuaresma, J., Lissner, T., Muttarak, R., Riahi, K., Theokritoff, E., Thomas, A., Van Maanen, N., and Byers, E.: Towards scenario representation of adaptive capacity for global climate change assessments, Nat. Clim. Change, 13, 778–787, https://doi.org/10.1038/s41558-023-01725-1, 2023.

Asadieh, B. and Krakauer, N. Y.: Global change in streamflow extremes under climate change over the 21st century, Hydrol. Earth Syst. Sci., 21, 5863–5874, https://doi.org/10.5194/hess-21-5863-2017, 2017.

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., and Silliman, B. R.: The value of estuarine and coastal ecosystem services, Ecol. Monogr., 81, 169–193, https://doi.org/10.1890/10-1510.1, 2011.

Beck, M. W., Losada, I. J., Menéndez, P., Reguero, B. G., Díaz-Simal, P., and Fernández, F.: The global flood protection savings provided by coral reefs, Nat. Commun., 9, 2186, https://doi.org/10.1038/s41467-018-04568-z, 2018.

Becken, S.: Water equity – Contrasting tourism water use with that of the local community, Water Resour. Ind., 7–8, 9–22, https://doi.org/10.1016/j.wri.2014.09.002, 2014.

Berrang-Ford, L., Siders, A. R., Lesnikowski, A., and et al.: A systematic global stocktake of evidence on human adaptation to climate change, Nat. Clim. Change, 11, 989–1000, https://doi.org/10.1038/s41558-021-01170-y, 2021.

Best, J.: Anthropogenic stresses on the world's big rivers, Nat. Geosci., 12, 7–21, https://doi.org/10.1038/s41561-018-0262-x, 2019.

Biemans, H., Haddeland, I., Kabat, P., Ludwig, F., Hutjes, R. W. A., Heinke, J., Von Bloh, W., and Gerten, D.: Impact of reservoirs on river discharge and irrigation water supply during the 20th century, Water Resour. Res., 47, 1–15, https://doi.org/10.1029/2009WR008929, 2011.

Bullister, J. L. and Warner, M. J.: Atmospheric Histories (1765-2022) for CFC-11, CFC-12, CFC-113, CCl4, SF6 and N2O, https://doi.org/10.3334/cdiac/otg.cfc_atm_hist_2015, 2017.

Campbell, B. M., Beare, D. J., Bennett, E. M., Hall-Spencer, J. M., Ingram, J. S. I., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J. A., and Shindell, D.: Agriculture production as a major driver of the Earth system exceeding planetary boundaries, Ecol. Soc., 22, https://doi.org/10.5751/es-09595-220408, 2017.

Chávez García Silva, R., Reinecke, R., Copty, N. K., Barry, D. A., Heggy, E., Labat, D., Roggero, P. P., Borchardt, D., Rode, M., Gómez-Hernández, J. J., and Jomaa, S.: Multi-decadal groundwater observations reveal surprisingly stable levels in southwestern Europe, Commun. Earth Environ., 5, 387, https://doi.org/10.1038/s43247-024-01554-w, 2024.

Chmura, G. L., Anisfeld, S. C., Cahoon, D. R., and Lynch, J. C.: Global carbon sequestration in tidal, saline wetland soils, Glob. Biogeochem. Cycles, 17, 1111, https://doi.org/10.1029/2002GB001917, 2003.

Citrini, A., Sangiorgio, M., and Rosa, L.: Global multi-model trends of unsustainable irrigation under climate change scenarios, Environ. Res. Lett., 20, 104011, https://doi.org/10.1088/1748-9326/adfcee, 2025.

Climate-ADAPT: Climate-ADAPT, https://climate-adapt.eea.europa.eu/en/data-and-downloads?, last access: 24 July 2026, 2026., 2026.

Colelli, F. P. and Cian, E. D.: Cooling demand in integrated assessment models: a methodological review, Environ. Res. Lett., 15, 113005, https://doi.org/10.1088/1748-9326/abb90a, 2020.

Colelli, F. P., Emmerling, J., Marangoni, G., Mistry, M. N., and De Cian, E.: Increased energy use for adaptation significantly impacts mitigation pathways, Nat. Commun., 13, 4964, https://doi.org/10.1038/s41467-022-32471-1, 2022.

Convention on Wetlands: Global Wetland Outlook 2025: Valuing, conserving, restoring and financing wetlands, First Edition., Secretariat of the Convention on Wetlands, Gland, Switzerland, https://doi.org/10.69556/GWO-2025-eng, 2025.

Costanza, J. K. and Terando, A. J.: Landscape Connectivity Planning for Adaptation to Future Climate and Land-Use Change, Curr. Landsc. Ecol. Rep., 4, 1–13, https://doi.org/10.1007/s40823-019-0035-2, 2019.

Daniel, J. S., Velders, G. J. M., Solomon, S., McFarland, M., and Montzka, S. A.: Present and future sources and emissions of halocarbons: Toward new constraints, J. Geophys. Res., 112, D02301, https://doi.org/10.1029/2006JD007275, 2007.

Davis, L. W. and Gertler, P. J.: Contribution of air conditioning adoption to future energy use under global warming, Proc. Natl. Acad. Sci., 112, 5962–5967, https://doi.org/10.1073/pnas.1423558112, 2015.

Davis, L. W. and Gertler, P. J.: Why Did Air Conditioning Adoption Accelerate Faster Than Predicted? Evidence from Mexico, w34101, National Bureau of Economic Research, Cambridge, MA, https://doi.org/10.3386/w34101, 2025.

deMenocal, P. B.: Climate and Human Evolution, Science, 331, 540–542, https://doi.org/10.1126/science.1190683, 2011.

Dixit, M. K. and Pradeep Kumar, P.: Embodied impacts of buildings from energy-carbon-water nexus perspective: A case study of university buildings, Clean. Energy Syst., 7, 100108, https://doi.org/10.1016/j.cles.2024.100108, 2024.

Donges, J. F., Heitzig, J., Barfuss, W., Kassel, J. A., Kittel, T., Kolb, J. J., Kolster, T., Müller-Hansen, F., Otto, I. M., Wiedermann, M., Zimmerer, K. B., and Lucht, W.: Earth system modelling with complex dynamic human societies: the copan:CORE World-Earth modeling framework, Earth Syst. Dyn., 11, 395–413, https://doi.org/10.5194/esd-2017-126, 2020.

Duan, H., Ming, X., Zhang, X.-B., Sterner, T., and Wang, S.: China's adaptive response to climate change through air-conditioning, iScience, 26, 106178, https://doi.org/10.1016/j.isci.2023.106178, 2023.

Ellis, E. C.: Ecology in an anthropogenic biosphere, Ecol. Monogr., 85, 287–331, https://doi.org/10.1890/14-2274.1, 2015.

Ember Climate: Countries and Regions, https://ember-climate.org/countries-and-regions/, last access: 19 July 2024, 2024., 2024.

Eriksen, S., Aldunce, P., Bahinipati, C. S., Martins, R. D., Molefe, J. I., Nhemachena, C., O'Brien, K., Olorunfemi, F., Park, J., Sygna, L., and Ulsrud, K.: When not every response to climate change is a good one: Identifying principles for sustainable adaptation, Clim. Dev., 3, 7–20, https://doi.org/10.3763/cdev.2010.0060, 2011.

FAO: Pesticides use and trade – 1990–2023, FAO, Rome, https://doi.org/10.4060/cd5968en, 2025.

Friess, D. A., Rogers, K., Lovelock, C. E., Krauss, K. W., Hamilton, S. E., Lee, S. Y., Lucas, R., Primavera, J., Rajkaran, A., and Shi, S.: The State of the World's Mangrove Forests: Past, Present, and Future, Annu. Rev. Environ. Resour., 44, 89–115, https://doi.org/10.1146/annurev-environ-101718-033302, 2019.

Galbraith, E. D., Faisal, A. A., Matitia, T., Fajzel, W., Hatton, I., Haberl, H., Krausmann, F., and Wiedenhofer, D.: Delineating the technosphere: definition, categorization, and characteristics, Earth Syst. Dyn., 16, 979–999, https://doi.org/10.5194/esd-16-979-2025, 2025.

Global Climate Observing System: Essential Climate Variables, https://gcos.wmo.int/en/essential-climate-variables/about, last access: 18 July 2024, 2024., 2024.

Green Cooling Initiative: Global greenhouse gas emissions from the RAC sector, https://www.green-cooling-initiative.org/country-data#!appliances-in-use/all-sectors/absolute, last access: 5 January 2026, 2024., 2024.

Gudmundsson, L., Boulange, J., Do, H. X., Gosling, S. N., Grillakis, M. G., Koutroulis, A. G., Leonard, M., Liu, J., Müller Schmied, H., Papadimitriou, L., Pokhrel, Y., Seneviratne, S. I., Satoh, Y., Thiery, W., Westra, S., Zhang, X., and Zhao, F.: Globally observed trends in mean and extreme river flow attributed to climate change, Science, 371, 1159–1162, https://doi.org/10.1126/science.aba3996, 2021.

Holman, I. P., Brown, C., Carter, T. R., Harrison, P. A., and Rounsevell, M.: Improving the representation of adaptation in climate change impact models, Reg. Environ. Change, 19, 711–721, https://doi.org/10.1007/s10113-018-1328-4, 2019.

IEA: The Future of Cooling, IEA, Paris, https://doi.org/10.1787/9789264301993-en, 2018.

IEA: Clean energy can help to ease the water crisis, https://www.iea.org/commentaries/clean-energy-can-help-to-ease-the-water-crisis, last access: 22 August 2024a, 2023., 2023.

IEA: Space Cooling: Net Zero Emissions Guide, https://www.iea.org/reports/space-cooling-2, last access: 21 August 2024b, 2023., 2023.

IEA: Buildings, https://www.iea.org/energy-system/buildings/space-cooling#tracking, last access: 21 August 2024a, 2024., 2024.

IEA: Energy demand for desalination in the Stated Policies Scenario, 1990-2030, https://www.iea.org/data-and-statistics/charts/energy-demand-for-desalination-in-the-stated-policies-scenario-1990-2030, last access: 19 July 2024b, 2024., 2024.

IEA: Heating, https://www.iea.org/energy-system/buildings/heating#tracking, last access: 13 July 2024c, 2024., 2024.

IEA: World Energy Outlook 2024, IEA, Paris, 2024d.

IPCC: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Cambridge University Press, Cambridge, 2022a.

IPCC: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: V. Masson-Delmotte, Zhai P., A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Cambridge University Press, Cambridge, 2022b.

IPCC: Summary for Policymakers, in: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: H.-O. Pörtner, D.C.

Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Cambridge University Press, Cambridge, 2022c.

IPCC and TEAP: Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons, Cambridge University Press, Cambridge, 2005.

Jägermeyr, J., Gerten, D., Heinke, J., Schaphoff, S., Kummu, M., and Lucht, W.: Water savings potentials of irrigation systems: global simulation of processes and linkages, Hydrol. Earth Syst. Sci., 19, 3073–3091, https://doi.org/10.5194/hess-19-3073-2015, 2015.

Jaramillo, F. and Destouni, G.: Local flow regulation and irrigation raise global human water consumption and footprint, Science, 350, 1248–1251, https://doi.org/10.1126/science.aad1010, 2015.

Jarvis, A. J., Jarvis, S. J., and Hewitt, C. N.: Resource acquisition, distribution and end-use efficiencies and the growth of industrial society, Earth Syst. Dyn., 6, 689–702, https://doi.org/10.5194/esd-6-689-2015, 2015.

Jasechko, S., Seybold, H., Perrone, D., Fan, Y., Shamsudduha, M., Taylor, R. G., Fallatah, O., and Kirchner, J. W.: Rapid groundwater decline and some cases of recovery in aquifers globally, Nature, 625, 715–721, https://doi.org/10.1038/s41586-023-06879-8, 2024.

Jones, E., Qadir, M., Van Vliet, M. T. H., Smakhtin, V., and Kang, S.: The state of desalination and brine production: A global outlook, Sci. Total Environ., 657, 1343–1356, https://doi.org/10.1016/j.scitotenv.2018.12.076, 2019.

Kassam, A., Derpsch, R., and Friedrich, T.: Global achievements in soil and water conservation: The case of Conservation Agriculture, Int. Soil Water Conserv. Res., 2, 5–13, https://doi.org/10.1016/S2095-6339(15)30009-5, 2014.

Keller, P. S., Marcé, R., Obrador, B., and Koschorreck, M.: Global carbon budget of reservoirs is overturned by the quantification of drawdown areas, Nat. Geosci., 14, 402–408, https://doi.org/10.1038/s41561-021-00734-z, 2021.

Kennard, H., Oreszczyn, T., Mistry, M., and Hamilton, I.: Population-weighted degree-days: The global shift between heating and cooling, Energy Build., 271, 1–9, https://doi.org/10.1016/j.enbuild.2022.112315, 2022.

Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Borken-Kleefeld, J., and Schöpp, W.: Global anthropogenic emissions of particulate matter including black carbon, Atmos. Chem. Phys., 17, 8681–8723, https://doi.org/10.5194/acp-17-8681-2017, 2017.

Laybourn, L., Evans, J., and Dyke, J.: Derailment risk: A systems analysis that identifies risks which could derail the sustainability transition, Earth Syst. Dyn., 14, 1171–1182, https://doi.org/10.5194/esd-14-1171-2023, 2023.

Lenton, T. M., Xu, C., Abrams, J. F., Ghadiali, A., Loriani, S., Sakschewski, B., Zimm, C., Ebi, K. L., Dunn, R. R., Svenning, J.-C., and Scheffer, M.: Quantifying the human cost of global warming, Nat. Sustain., 6, 1237–1247, https://doi.org/10.1038/s41893-023-01132-6, 2023.

Levia, D. F., Creed, I. F., Hannah, D. M., Nanko, K., Boyer, E. W., Carlyle-Moses, D. E., Van De Giesen, N., Grasso, D., Guswa, A. J., Hudson, J. E., Hudson, S. A., Iida, S., Jackson, R. B., Katul, G. G., Kumagai, T., Llorens, P., Ribeiro, F. L., Pataki, D. E., Peters, C. A., Carretero, D. S., Selker, J. S., Tetzlaff, D., Zalewski, M., and Bruen, M.: Homogenization of the terrestrial water cycle, Nat. Geosci., 13, 656–658, https://doi.org/10.1038/s41561-020-0641-y, 2020.

Lickley, M., Solomon, S., Fletcher, S., Velders, G. J. M., Daniel, J., Rigby, M., Montzka, S. A., Kuijpers, L. J. M., and Stone, K.: Quantifying contributions of chlorofluorocarbon banks to emissions and impacts on the ozone layer and climate, Nat. Commun., 11, 1380, https://doi.org/10.1038/s41467-020-15162-7, 2020.

Littlefield, C. E., Krosby, M., Michalak, J. L., and Lawler, J. J.: Connectivity for species on the move: supporting climate-driven range shifts, Front. Ecol. Environ., 17, 270–278, https://doi.org/10.1002/fee.2043, 2019.

Lobell, D. B., Bonfils, C., and Faurès, J.-M.: The Role of Irrigation Expansion in Past and Future Temperature Trends, Earth Interact., 12, 1–11, https://doi.org/10.1175/2007ei241.1, 2008.

Lovelock, J. E.: Gaia as seen through the atmosphere, Atmos. Environ., 6, 579–580, https://doi.org/10.1016/0004-6981(72)90076-5, 1972.

Lovelock, J. E. and Margulis, L.: Atmospheric homeostasis by and for the biosphere: the gaia hypothesis, Tellus, 26, 2–10, https://doi.org/10.1111/j.2153-3490.1974.tb01946.x, 1974.

Lu, C. and Tian, H.: Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance, Earth Syst. Sci. Data, 9, 181–192, https://doi.org/10.5194/essd-9-181-2017, 2017.

Magni, M., Jones, E. R., Bierkens, M. F. P., and Van Vliet, M. T. H.: Global energy consumption of water treatment technologies, Water Res., 277, 123245, https://doi.org/10.1016/j.watres.2025.123245, 2025.

McDermid, S., Nocco, M., Lawston-Parker, P., Keune, J., Pokhrel, Y., Jain, M., Jägermeyr, J., Brocca, L., Massari, C., Jones, A. D., Vahmani, P., Thiery, W., Yao, Y., Bell, A., Chen, L., Dorigo, W., Hanasaki, N., Jasechko, S., Lo, M.-H., Mahmood, R., Mishra, V., Mueller, N. D., Niyogi, D., Rabin, S. S., Sloat, L., Wada, Y., Zappa, L., Chen, F., Cook, B. I., Kim, H., Lombardozzi, D., Polcher, J., Ryu, D., Santanello, J., Satoh, Y., Seneviratne, S., Singh, D., and Yokohata, T.: Irrigation in the Earth system, Nat. Rev. Earth Environ., 4, 435–453, https://doi.org/10.1038/s43017-023-00438-5, 2023.

McGuire, J. L., Lawler, J. J., McRae, B. H., Nuñez, T. A., and Theobald, D. M.: Achieving climate connectivity in a fragmented landscape, Proc. Natl. Acad. Sci., 113, 7195–7200, https://doi.org/10.1073/pnas.1602817113, 2016.

Mehta, P., Siebert, S., Kummu, M., Deng, Q., Ali, T., Marston, L., Xie, W., and Davis, K. F.: Half of twenty-first century global irrigation expansion has been in water-stressed regions, Nat. Water, 2, 254–261, https://doi.org/10.1038/s44221-024-00206-9, 2024.

Merschroth, S., Miatto, A., Weyand, S., Tanikawa, H., and Schebek, L.: Lost Material Stock in Buildings due to Sea Level Rise from Global Warming: The Case of Fiji Islands, Sustainability, 12, 834, https://doi.org/10.3390/su12030834, 2020.

Midgley, T. Jr. and Henne, A. L.: Organic Fluorides as Refrigerants, Ind. Eng. Chem., 22, 542–545, https://doi.org/10.1021/ie50245a031, 1930.

Möhring, N., Ba, M. N., Braga, A. R. C., Gaba, S., Gagic, V., Kudsk, P., Larsen, A., Mesnage, R., Niggli, U., Qaim, M., Schreinemachers, P., Stamm, C., de Vries, W., and Finger, R.: Expected effects of a global transformation of agricultural pest management, Nat. Commun., 16, 10901, https://doi.org/10.1038/s41467-025-66982-4, 2025.

Molina, M. J. and Rowland, F. S.: Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone, Nature, 249, 810–812, https://doi.org/10.1038/249810a0, 1974.

Morelli, T. L., Barrows, C. W., Ramirez, A. R., Cartwright, J. M., Ackerly, D. D., Eaves, T. D., Ebersole, J. L., Krawchuk, M. A., Letcher, B. H., Mahalovich, M. F., Meigs, G. W., Michalak, J. L., Millar, C. I., Quiñones, R. M., Stralberg, D., and Thorne, J. H.: Climate-change refugia: biodiversity in the slow lane, Front. Ecol. Environ., 18, 228–234, https://doi.org/10.1002/fee.2189, 2020.

Morris, R. L., Konlechner, T. M., Ghisalberti, M., and Swearer, S. E.: From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence, Glob. Change Biol., 24, 1827–1842, https://doi.org/10.1111/gcb.14063, 2018.

Nieuwkamer, R., Kox, M., Fiselier, J., van Wieringen, D. R. G., Tonneijck, F., Cronin, K., and ten Bosch, W.: Reducing the ecosystem-based carbon footprint of coastal engineering, Wetlands International, 2022.

Niinimäki, K., Peters, G., Dahlbo, H., Perry, P., Rissanen, T., and Gwilt, A.: The environmental price of fast fashion, Nat. Rev. Earth Environ., 1, 189–200, https://doi.org/10.1038/s43017-020-0039-9, 2020.

Nordhaus, W. D.: To Slow or Not to Slow: The Economics of The Greenhouse Effect, Econ. J., 101, 920–937, https://doi.org/10.2307/2233864, 1991.

Obradovich, N. and Rahwan, I.: Risk of a feedback loop between climatic warming and human mobility, J. R. Soc. Interface, 16, 20190058, https://doi.org/10.1098/rsif.2019.0058, 2019.

Ott, B., Donges, J. F., and Rockström, J.: Climate Adaptation in the Anthropocene: Towards an Earth System-Based Perspective, Rev., 2026.

Ou, Z., He, F., Zhu, Y., Lu, P., and Wang, L.: Analysis of driving factors of water demand based on explainable artificial intelligence, J. Hydrol. Reg. Stud., 47, 101396, https://doi.org/10.1016/j.ejrh.2023.101396, 2023.

Pavanello, F., De Cian, E., Davide, M., Mistry, M., Cruz, T., Bezerra, P., Jagu, D., Renner, S., Schaeffer, R., and Lucena, A. F. P.: Air-conditioning and the adaptation cooling deficit in emerging economies, Nat. Commun., 12, 6460, https://doi.org/10.1038/s41467-021-26592-2, 2021.

PBScience: Planetary Health Check 2025, Potsdam Institute for Climate Impact Research (PIK), Potsdam, https://doi.org/10.48485/pik.2025.017, 2025.

Piemontese, L., Castelli, G., Fetzer, I., Barron, J., Liniger, H., Harari, N., Bresci, E., and Jaramillo, F.: Estimating the global potential of water harvesting from successful case studies, Glob. Environ. Change, 63, 102121, https://doi.org/10.1016/j.gloenvcha.2020.102121, 2020.

Porkka, M., Virkki, V., Wang-Erlandsson, L., Gerten, D., Gleeson, T., Mohan, C., Fetzer, I., Jaramillo, F., Staal, A., Te Wierik, S., Tobian, A., Van Der Ent, R., Döll, P., Flörke, M., Gosling, S. N., Hanasaki, N., Satoh, Y., Müller Schmied, H., Wanders, N., Famiglietti, J. S., Rockström, J., and Kummu, M.: Notable shifts beyond pre-industrial streamflow and soil moisture conditions transgress the planetary boundary for freshwater change, Nat. Water, 2, 262–273, https://doi.org/10.1038/s44221-024-00208-7, 2024.

Puy, A., Sheikholeslami, R., Gupta, H. V., Hall, J. W., Lankford, B., Lo Piano, S., Meier, J., Pappenberger, F., Porporato, A., Vico, G., and Saltelli, A.: The delusive accuracy of global irrigation water withdrawal estimates, Nat. Commun., 13, 3183, https://doi.org/10.1038/s41467-022-30731-8, 2022.

Puy, A., Linga, S. N., Wei, N., Flinders, S., Callow, B., Allen, G., Cross, B., Aguiló-Rivera, C., and Lankford, B.: Widely cited global irrigation statistics lack empirical support, PNAS Nexus, 4, pgaf323, https://doi.org/10.1093/pnasnexus/pgaf323, 2025.

Qin, J., Duan, W., Zou, S., Chen, Y., Huang, W., and Rosa, L.: Global energy use and carbon emissions from irrigated agriculture, Nat. Commun., 15, 3084, https://doi.org/10.1038/s41467-024-47383-5, 2024.

Rahman, M. A., Pawijit, Y., Xu, C., Moser-Reischl, A., Pretzsch, H., Rötzer, T., and Pauleit, S.: A comparative analysis of urban forests for storm-water management, Sci. Rep., 13, 1451, https://doi.org/10.1038/s41598-023-28629-6, 2023.

Ravishankara, A. R., Daniel, J. S., and Portmann, R. W.: Nitrous Oxide (N2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century, Science, 326, 123–125, https://doi.org/10.1126/science.1176985, 2009.

Richards, D. R., Thompson, B. S., and Wijedasa, L.: Quantifying net loss of global mangrove carbon stocks from 20 years of land cover change, Nat. Commun., 11, 4260, https://doi.org/10.1038/s41467-020-18118-z, 2020.

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M., Rahmstorf, S., Schaphoff, S., Thonicke, K., Tobian, A., Virkki, V., Wang-Erlandsson, L., Weber, L., and Rockström, J.: Earth beyond six of nine planetary boundaries, Sci. Adv., 9, eadh2458, https://doi.org/10.1126/sciadv.adh2458, 2023.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., and Foley, J. A.: A safe operating space for humanity, Nature, 461, 472–475, https://doi.org/10.1038/461472a, 2009.

Rockström, J., Thilsted, S. H., Willett, W. C., Gordon, L. J., Herrero, M., Hicks, C. C., Mason-D'Croz, D., Rao, N., Springmann, M., Wright, E. C., Agustina, R., Bajaj, S., Bunge, A. C., Carducci, B., Conti, C., Covic, N., Fanzo, J., Forouhi, N. G., Gibson, M. F., Gu, X., Kebreab, E., Kremen, C., Laila, A., Laxminarayan, R., Marteau, T. M., Monteiro, C. A., Norberg, A., Njuki, J., Oliveira, T. D., Pan, W.-H., Rivera, J. A., Robinson, J. P. W., Sundiang, M., te Wierik, S., van Vuuren, D. P., Vermeulen, S., Webb, P., Alqodmani, L., Ambikapathi, R., Barnhill, A., Baudish, I., Beier, F., Beillouin, D., Beusen, A. H. W., Breier, J., Chemarin, C., Chepeliev, M., Clapp, J., de Vries, W., Pérez-Domínguez, I., Estrada-Carmona, N., Gerten, D., Golden, C. D., Jones, S. K., Jørgensen, P. S., Kozicka, M., Lotze-Campen, H., Maggi, F., Marzi, E., Mishra, A., Orduna-Cabrera, F., Popp, A., Schulte-Uebbing, L., Stehfest, E., Tang, F. H. M., Tsuchiya, K., Van Zanten, H. H. E., van Zeist, W.-J., Zhao, X., and DeClerck, F.: The EAT–Lancet Commission on healthy, sustainable, and just food systems, The Lancet, 406, 1625–1700, https://doi.org/10.1016/S0140-6736(25)01201-2, 2025.

Rosa, L.: Adapting agriculture to climate change via sustainable irrigation: biophysical potentials and feedbacks, Environ. Res. Lett., 17, 063008, https://doi.org/10.1088/1748-9326/ac7408, 2022.

Rosa, L., Gabrielli, P., and Sangiorgio, M.: Global energy, costs, and emissions from reverse osmosis desalination under future water scarcity, Water Res., 289, 124825, https://doi.org/10.1016/j.watres.2025.124825, 2026.

Salamanca, F., Georgescu, M., Mahalov, A., Moustaoui, M., and Wang, M.: Anthropogenic heating of the urban environment due to air conditioning, J. Geophys. Res. Atmos., 119, 5949–5965, https://doi.org/10.1002/2013JD021225, 2014.

Saura, S., Bertzky, B., Bastin, L., Battistella, L., Mandrici, A., and Dubois, G.: Protected area connectivity: Shortfalls in global targets and country-level priorities, Biol. Conserv., 219, 53–67, https://doi.org/10.1016/j.biocon.2017.12.020, 2018.

Saura, S., Bertzky, B., Bastin, L., Battistella, L., Mandrici, A., and Dubois, G.: Global trends in protected area connectivity from 2010 to 2018, Biol. Conserv., 238, 108183, https://doi.org/10.1016/j.biocon.2019.07.028, 2019.

Scanlon, B. R., Fakhreddine, S., Rateb, A., de Graaf, I., Famiglietti, J., Gleeson, T., Grafton, R. Q., Jobbagy, E., Kebede, S., Kolusu, S. R., Konikow, L. F., Long, D., Mekonnen, M., Schmied, H. M., Mukherjee, A., MacDonald, A., Reedy, R. C., Shamsudduha, M., Simmons, C. T., Sun, A., Taylor, R. G., Villholth, K. G., Vörösmarty, C. J., and Zheng, C.: Global water resources and the role of groundwater in a resilient water future, Nat. Rev. Earth Environ., 4, 87–101, https://doi.org/10.1038/s43017-022-00378-6, 2023.

Siebert, S., Kummu, M., Porkka, M., Döll, P., Ramankutty, N., and Scanlon, B.: A global data set of the extent of irrigated land from 1900 to 2005, Hydrol. Earth Syst. Sci., 19, 1521–1545, https://doi.org/10.5194/hess-19-1521-2015, 2015.

Sims, M. J., Stanimirova, R., Raichuk, A., Neumann, M., Richter, J., Follett, F., MacCarthy, J., Lister, K., Randle, C., Sloat, L., Esipova, E., Jupiter, J., Stanton, C., Morris, D., Melhart Slay, C., Purves, D., and Harris, N.: Global drivers of forest loss at 1 km resolution, Environ. Res. Lett., 20, 074027, https://doi.org/10.1088/1748-9326/add606, 2025.

Smith, S. J., Van Aardenne, J., Klimont, Z., Andres, R. J., Volke, A., and Delgado Arias, S.: Anthropogenic sulfur dioxide emissions: 1850–2005, Atmos. Chem. Phys., 11, 1101–1116, https://doi.org/10.5194/acp-11-1101-2011, 2011.

Song, C., Gardner, K. H., Klein, S. J. W., Souza, S. P., and Mo, W.: Cradle-to-grave greenhouse gas emissions from dams in the United States of America, Renew. Sustain. Energy Rev., 90, 945–956, https://doi.org/10.1016/j.rser.2018.04.014, 2018.

Song, S., Ding, Y., Li, W., Meng, Y., Zhou, J., Gou, R., Zhang, C., Ye, S., Saintilan, N., Krauss, K. W., Crooks, S., Lv, S., and Lin, G.: Mangrove reforestation provides greater blue carbon benefit than afforestation for mitigating global climate change, Nat. Commun., 14, 756, https://doi.org/10.1038/s41467-023-36477-1, 2023.

Statt, T. G.: Use of chlorofluorocarbons in refrigeration, insulation and mobile air conditioning in the USA, Int. J. Refrig., 11, 224–228, https://doi.org/10.1016/0140-7007(88)90077-1, 1988.

Steffen, W., Crutzen, P. J., and McNeill, J. R.: The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature, AMBIO J. Hum. Environ., 36, 614–621, 2007.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., De Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., and Sörlin, S.: Planetary boundaries: Guiding human development on a changing planet, Science, 347, 1259855, https://doi.org/10.1126/science.1259855, 2015a.

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., and Ludwig, C.: The trajectory of the anthropocene: The great acceleration, Anthr. Rev., 2, 81–98, https://doi.org/10.1177/2053019614564785, 2015b.

Stern, N.: The Economics of Climate Change: The Stern Review, Cambridge University Press, Cambridge, 2007.

Su, Q., Kambale, R. D., Tzeng, J.-H., Amy, G. L., Ladner, D. A., and Karthikeyan, R.: The growing trend of saltwater intrusion and its impact on coastal agriculture: Challenges and opportunities, Sci. Total Environ., 966, 178701, https://doi.org/10.1016/j.scitotenv.2025.178701, 2025.

Sun, Y.-Y., Faturay, F., Lenzen, M., Gössling, S., and Higham, J.: Drivers of global tourism carbon emissions, Nat. Commun., 15, 10384, https://doi.org/10.1038/s41467-024-54582-7, 2024.

Symmes, R., Fishman, T., Telesford, J. N., Singh, S. J., Tan, S., and De Kroon, K.: The weight of islands: Leveraging Grenada's material stocks to adapt to climate change, J. Ind. Ecol., 24, 369–382, https://doi.org/10.1111/jiec.12853, 2020.

Tanikawa, H., Managi, S., and Lwin, C. M.: Estimates of Lost Material Stock of Buildings and Roads Due to the Great East Japan Earthquake and Tsunami, J. Ind. Ecol., 18, 421–431, https://doi.org/10.1111/jiec.12126, 2014.

Teo, H. C., Zeng, Y., Sarira, T. V., Fung, T. K., Zheng, Q., Song, X. P., Chong, K. Y., and Koh, L. P.: Global urban reforestation can be an important natural climate solution, Environ. Res. Lett., 16, 034059, https://doi.org/10.1088/1748-9326/abe783, 2021.

UNEP: 2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector, United Nations Environment Programme, Nairobi, 2022.

UNEP: Global Cooling Watch 2023: Keeping it Chill: How to meet cooling demands while cutting emissions, United Nations Environment Programme, Nairobi, https://doi.org/10.59117/20.500.11822/44243, 2023.

UNEP: Adaptation Gap Report 2024: Come hell and high water — As fires and floods hit the poor hardest, it is time for the world to step up adaptation actions., United Nations Environment Programme, Nairobi, https://doi.org/10.59117/20.500.11822/46497, 2024.

UNEP: Adaptation Gap Report 2025: Running on Empty - The World is Gearing up for Climate Resilience — without the Money to get there, United Nations Environment Programme, Nairobi, https://doi.org/10.59117/20.500.11822/48798, 2025a.

UNEP: Global Cooling Watch 2025: The Free Degrees, United Nations Environment Programme, Nairobi, https://doi.org/10.59117/20.500.11822/48926, 2025b.

UNEP: Global Status Report for Buildings and Construction 2024/25: Not just another brick in the wall, United Nations Environment Programme, Nairobi, 2025c.

UN-Habitat and WHO: Progress on the proportion of domestic and industrial wastewater flows safely treated – Mid-term status of SDG Indicator 6.3.1 and acceleration needs, with a special focus on climate change, wastewater reuse and health., UN-Habitat and WHO, 2024.

Van Maanen, N., Lissner, T., Harmsen, M., Piontek, F., Andrijevic, M., and Van Vuuren, D. P.: Representation of adaptation in quantitative climate assessments, Nat. Clim. Change, 13, 309–311, https://doi.org/10.1038/s41558-023-01644-1, 2023.

Van Ruijven, B. J., De Cian, E., and Sue Wing, I.: Amplification of future energy demand growth due to climate change, Nat. Commun., 10, 2762, https://doi.org/10.1038/s41467-019-10399-3, 2019.

Vattioni, S., Peter, T., Weber, R., Dykema, J. A., Luo, B., Stenke, A., Feinberg, A., Sukhodolov, T., Keutsch, F. N., Ammann, M., Vockenhuber, C., Döbeli, M., Kelesidis, G. A., and Chiodo, G.: Injecting solid particles into the stratosphere could mitigate global warming but currently entails great uncertainties, Commun. Earth Environ., 6, 132, https://doi.org/10.1038/s43247-025-02038-1, 2025.

Velders, G. J. M., Andersen, S. O., Daniel, J. S., Fahey, D. W., and McFarland, M.: The importance of the Montreal Protocol in protecting climate, Proc. Natl. Acad. Sci., 104, 4814–4819, https://doi.org/10.1073/pnas.0610328104, 2007.

Velders, G. J. M., Daniel, J. S., Montzka, S. A., Vimont, I., Rigby, M., Krummel, P. B., Muhle, J., O'Doherty, S., Prinn, R. G., Weiss, R. F., and Young, D.: Projections of hydrofluorocarbon (HFC) emissions and the resulting global warming based on recent trends in observed abundances and current policies, Atmos. Chem. Phys., 22, 6087–6101, https://doi.org/10.5194/acp-22-6087-2022, 2022.

Viguié, V., Juhel, S., Ben-Ari, T., Colombert, M., Ford, J. D., Giraudet, L. G., and Reckien, D.: When adaptation increases energy demand: A systematic map of the literature, Environ. Res. Lett., 16, 033004, https://doi.org/10.1088/1748-9326/abc044, 2021.

Virkki, V., Andersen, L. S., Te Wierik, S., Gerten, D., and Porkka, M.: Regionally divergent drivers behind transgressions of the freshwater change planetary boundary, Nat. Commun., 17, 5132, https://doi.org/10.1038/s41467-026-73051-x, 2026.

Wada, Y. and Bierkens, M. F. P.: Sustainability of global water use: past reconstruction and future projections, Environ. Res. Lett., 9, 104003, https://doi.org/10.1088/1748-9326/9/10/104003, 2014.

Wada, Y., Wisser, D., Eisner, S., Flörke, M., Gerten, D., Haddeland, I., Hanasaki, N., Masaki, Y., Portmann, F. T., Stacke, T., Tessler, Z., and Schewe, J.: Multimodel projections and uncertainties of irrigation water demand under climate change, Geophys. Res. Lett., 40, 4626–4632, https://doi.org/10.1002/grl.50686, 2013.

WMO: Scientific Assessment of Ozone Depletion 2022, WMO, Geneva, 2022.

Young, M. D., Ros, G. H., and de Vries, W.: Impacts of agronomic measures on crop, soil, and environmental indicators: A review and synthesis of meta-analysis, Agric. Ecosyst. Environ., 319, 107551, https://doi.org/10.1016/j.agee.2021.107551, 2021.

Yuan, Q., Liu, Y., Qie, Y., Hu, C., Meng, Y., and Luan, F.: Unlocking global rainwater harvesting potential for safe drinking water access, Nat. Commun., 16, 11320, https://doi.org/10.1038/s41467-025-66429-w, 2025.

Yücel, S. G., Liang, Y., Wang, D., and Schwanen, T.: Adapting everyday activities to summer heatwaves: a multi-country analysis of mobile phone location data, Environ. Res. Clim., 5, 025007, https://doi.org/10.1088/2752-5295/ae4cc2, 2026.

Zhong, X., Hu, M., Deetman, S., Steubing, B., Lin, H. X., Hernandez, G. A., Harpprecht, C., Zhang, C., Tukker, A., and Behrens, P.: Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060, Nat. Commun., 12, 6126, https://doi.org/10.1038/s41467-021-26212-z, 2021.