CHAPTER 2

The role of freshwater in climate mitigation: Biophysical interdependencies

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Storm clouds. Source: Josh Sorenson, Unsplash.

Highlights

- The climate system and water cycle are deeply intertwined. Climate mitigation measures needed to achieve the goals of the Paris Agreement fundamentally depend on, and impact, freshwater resources and the water cycle.
- In terms of dependence, a functioning freshwater cycle is crucial to sustain the water security needed for climate mitigation measures to reach their full potential. For example, water stress can hamper energy production from hydropower as well as trigger carbon release from forests, thwarting climate mitigation effects expected from protecting or managing these systems.
- In terms of impact, climate mitigation measures directly modify land, climate, and water quality and quantity, with potentially adverse outcomes. These changes happen on top of already shifting freshwater dynamics, such as droughts and floods caused by ongoing climate change. Combined, they could potentially trigger abrupt and irreversible ecohydrologic regime shifts that may not only affect the implementation and success of mitigation measures but also threaten water security as the foundation of life for humans and ecosystems.
- In the dynamic and hyperconnected Anthropocene era, the relationships between water and climate mitigation can be remote, complex, and non-linear. Holistic systems thinking approaches are thus needed to account for the role of freshwater in climate mitigation to enable decisive and sustainable climate action.

2.1 Introduction

The water cycle is a crucial part of the planetary system. The water cycle supports the living world by enabling photosynthesis, transporting nutrients, and regulating temperature and wind patterns. The Earth systems – land, ocean, atmosphere, and ice – are fundamentally connected and regulated by the freshwater cycle (Gleeson et al. 2020). At the same time, water is very sensitive to climate change and land-use change, which result in altered water flows and availability. This means freshwater stocks and flows are both driving and being impacted by changes in the Earth system, including the climate. In the policy and governance realm of climate change, however, freshwater is mentioned mainly as an interface for the impacts of climate change in the context of climate adaptation (IPCC 2022a; 2022b). However, the role of water as a driver in the climate system, and crucial precondition and lever to climate mitigation, is frequently overlooked (IPCC 2022b). Understanding the role of water in climate mitigation creates a need to look at water in all its guises. While management of surface water resources tends to be in focus, invisible water in the soil and atmosphere gets relatively little attention (Keys et al. 2017; Rockström et al. 2010; Wierik et al. 2020).

This chapter explains – from a biophysical Earth system perspective – why freshwater cycle dynamics should be accounted for in climate mitigation. First, it provides an introductory explanation of the role of the freshwater cycle in the Earth system based on current scientific understanding (Box 2.1). Then, it presents the climate mitigation measures in focus in this report, covering interventions in land-based and freshwater ecosystems; the energy sector; and water, sanitation, and hygiene (WASH) sector (Section 2.2). Based on Earth system knowledge, we unpack how key mitigation measures impact and depend on freshwater and freshwater-dependent ecosystems (Section 2.3). Finally, this chapter describes why rapid and water-smart climate mitigation is important for avoiding potentially persistent and abrupt shifts in social, hydrological, and ecological systems (Section 2.4).

Box 2.1. The global water cycle as the bloodstream of the Earth system

Freshwater is in constant movement regulated by land-based and freshwater ecosystems, atmospheric processes, and anthropogenic activities. Water from the oceans evaporates to supply the atmosphere with water vapour, form clouds and precipitate as rain or snow. Precipitation over land may infiltrate the ground to provide soil moisture, recharge groundwater stocks, and create surface runoff that flows to rivers, lakes, wetlands, and reservoirs.

The continuous movement of freshwater is critical to all terrestrial lifeforms, including the enabling of photosynthesis and biomass production. At the same time, freshwater flows occur thanks to vegetation activities that pump soil moisture into the atmosphere, thereby creating enormous water flows despite relatively small freshwater stocks in the atmosphere, soil, and other liquid water bodies (Figure 2.1). For example, atmospheric moisture volume at any given time is on average around 13,000 cubic kilometres (km³), but serves the transport of around 470,000 km³/year of oceanic evaporation, 424,000 km³/year of oceanic precipitation, 46,000 km³/year water vapour transport from ocean to land, 120,000 km³/year terrestrial precipitation over land, and 74,000 km³/year total terrestrial evaporation (Douville et al. 2021; IPCC 2022c). Water in rivers, lakes, and groundwater is referred to as blue water, whereas plant-available water in soil is referred to as green water. Blue water is used for irrigation, hydropower, and societal water use, and green water is critical for terrestrial ecosystems and most of the world's agriculture and food production (Falkenmark and Rockström 2006).

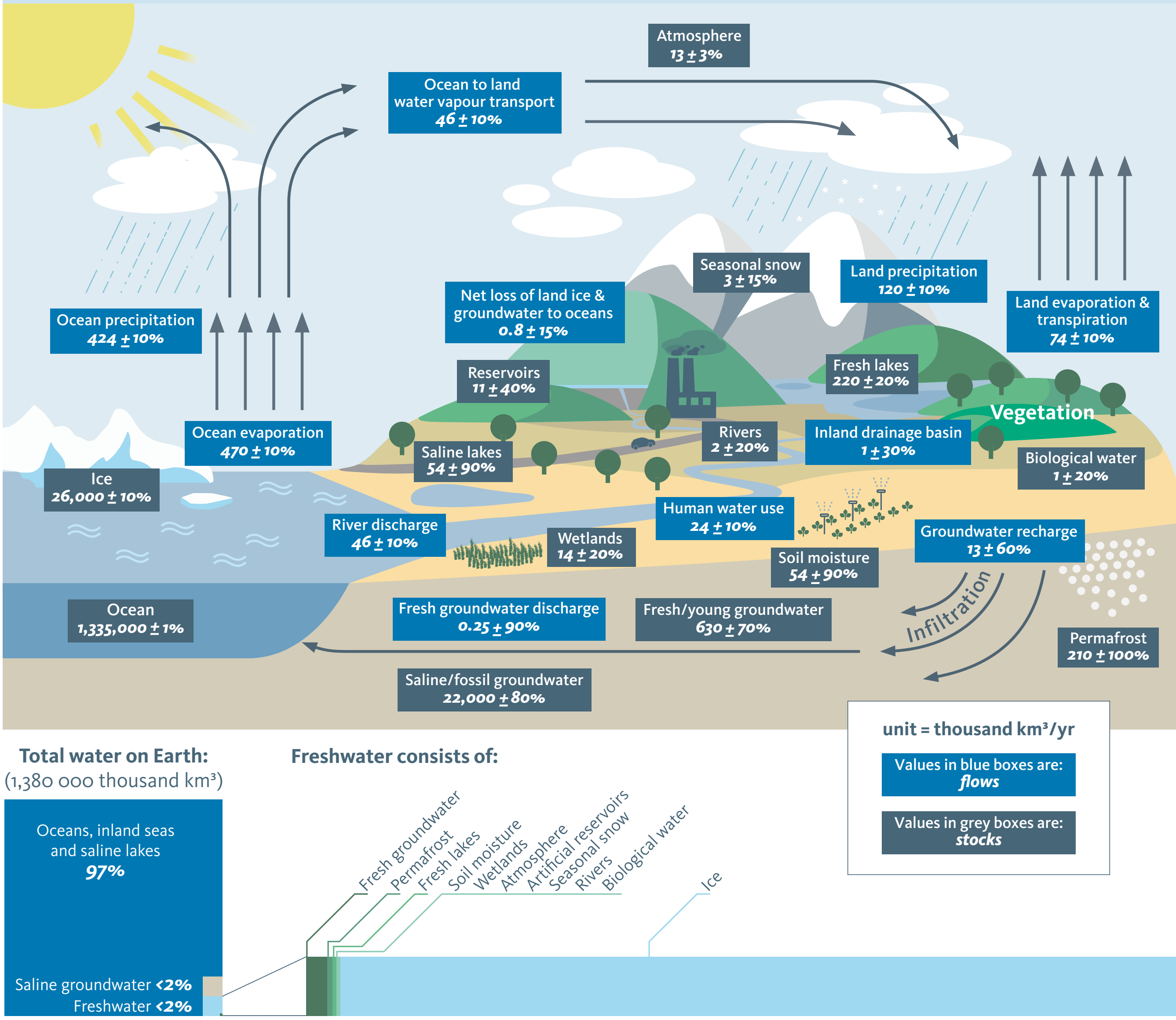

Figure 2.1. The global water cycle with estimates of water flows and stocks. Numbers from IPCC AR6 Chapter 8 Fig 8.1. https://www.ipcc.ch/report/ar6/wg1/figures/chapter-8. Graphic adapted from GIZ (2020), with quantitative estimates synthesized by Douville et al (2021).

Box 2.1. Cont.

Freshwater vapour feedbacks connect upwind evaporation to downwind rainfall, which means that land use in upwind areas has implications for downwind water resources, and potentially further cascading impacts on downwind ecosystems and the water cycle. On a global average, 60 per cent of land evaporation (of which 60 per cent comes from vegetation transpiration and the rest from evaporation from soil and vegetation canopies) recycles and contributes to precipitation over land again; and 40 per cent of land precipitation originates from land evaporation. In some areas, such as in large parts of Eurasia, southern South America, and West and Central Africa, the vast majority of land precipitation has a terrestrial origin and thus depends heavily on terrestrial vegetation activities for producing the moisture that supplies its rainfall (Keys et al. 2016; van der Ent et al. 2010). The upwind lands that supply moisture for an area of interest can be referred to as 'precipitationshed' (Keys et al. 2012). Freshwater systems thus do not respect administrative boundaries and extend far beyond the catchment or river basin scale.

2.2 Bloodstream of the Earth: The fundamental functions of freshwater in the Earth system

Freshwater is crucial to the functioning of the entire Earth system. The holistic systems perspective taken in this report is grounded in the scientific understanding that the freshwater cycle is an integral part of the Earth system, which comprises the land, the ocean, the atmosphere, and ice and glaciers (Box 2.1).

Freshwater serves four major Earth system functions: storage, transport, hydro-ecological regulation, and hydro-climatic regulation (Figure 2.2). Of all water on Earth, only 1 per cent of freshwater is available to ecosystems and societies, with the rest stored in oceans (97 per cent) or bound in ice and deep groundwater. Both the available and unavailable freshwater storage is critical, for example for regulating sea levels, sustaining base flows to rivers, and buffering fluctuations in water availability. Importantly, driven by the sun, freshwater is in constant movement, allowing its role in the Earth system and for climate mitigation to go far beyond its relevance in terms of availability to ecosystems and societies. As an agent of transport, freshwater moves sediments, nutrients, and carbon, thereby shaping landscapes, nutrient cycles, and carbon cycles. Moreover, the spatial and temporal distribution and movement of freshwater are essential for supporting and regulating ecological functions on land and water. Freshwater directly supports land-based life by enabling physiological processes such as photosynthesis, and aquatic life by providing freshwater habitats such as rivers, lakes, wetlands, and coastal systems. Finally, freshwater regulates climate across different scales by modifying the energy balance,[1] since moisture content regulates cloud formation,[2] surface temperature, the land-ocean temperature gradient, and atmospheric turbulence and circulation. For example, droughts can drive fires, irrigation can delay monsoon onset, and high humidity can lead to deadly heatwaves that are beyond human physiological tolerance (Russo et al. 2017).

Freshwater also serves its hydro-climatic function through intertwinements with the global carbon and methane budgets; i.e., the two types of greenhouse gases (GHG) with the largest influence on anthropogenic global warming. Carbon dioxide can persist in the atmosphere for thousands of years, and emissions therefore accumulate. Fossil fuel production and use is the largest carbon emitter by far, followed by land-use change. Oceans, soils, and vegetation are currently the largest carbon sinks, and human removal of carbon from the atmosphere in the future will be necessary to limit climate change to 1.5 to 2°C (above pre-industrial levels).

1. The Earth maintains a stable temperature over time if the net incoming energy from the sun is balanced by the net outgoing energy from the Earth. The incoming energy from the sun is unevenly distributed, and the regional temperature and climate depends on energy redistribution across the Earth system.
2. Clouds block sunlight and help cool the planet as a whole, although clouds can also trap more heat than they reflect. Whether in the future clouds will contribute to warming or cooling at the global and regional scales is an active area of research.

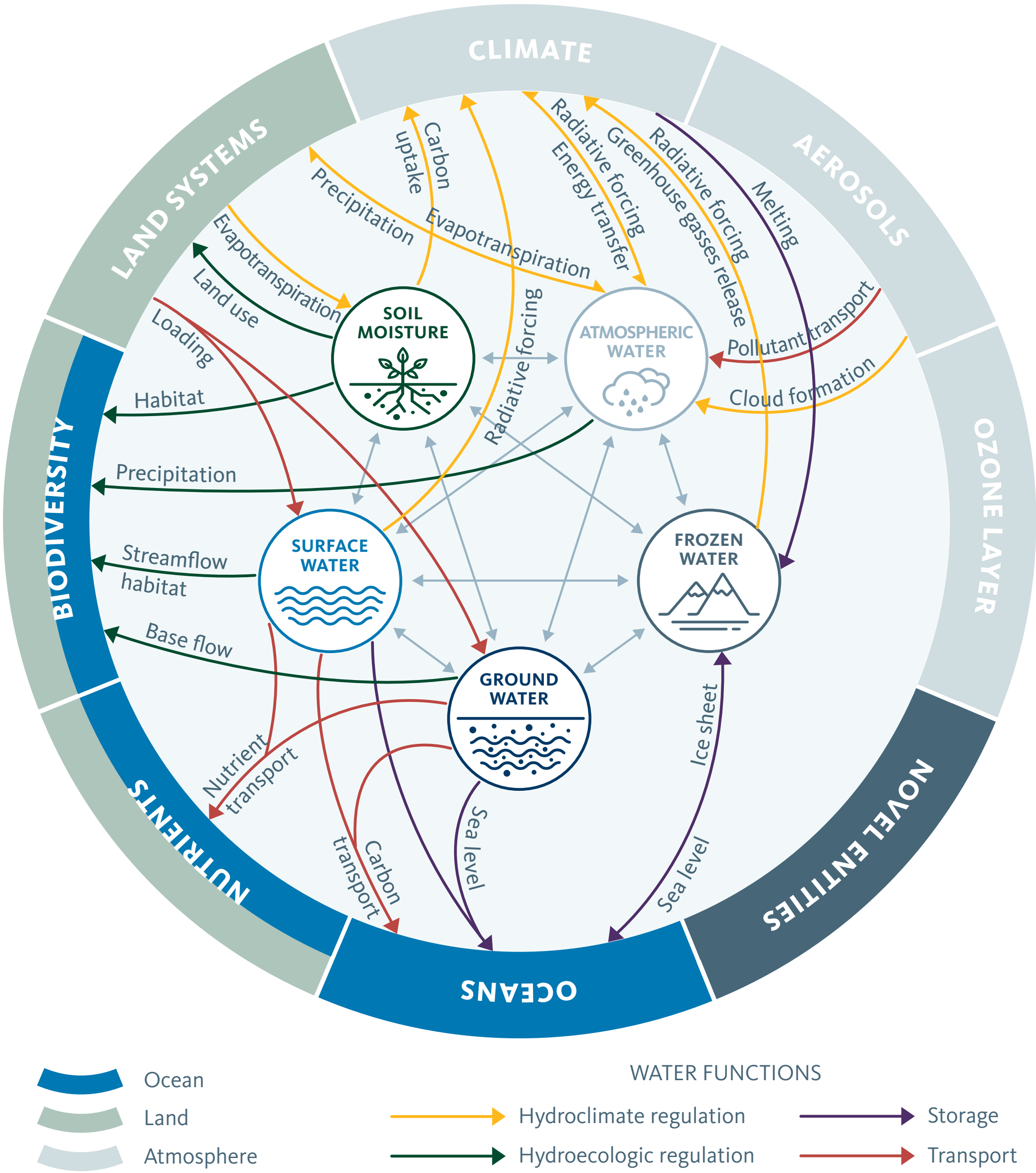

Figure 2.2. Four core Earth system functions of freshwater. The five major stores of water (soil moisture, atmospheric water, frozen water, groundwater, and surface water) interact substantially with all components of the Earth system. Source: Gleeson et al. (2020).

Methane is ~30 times more potent than carbon in a 100 years perspective, but it is short-lived in the atmosphere (~12 years). Agriculture, wetlands, and different forms of waste are the largest methane emitters, followed by fossil production and use (Figure 2.3). Worryingly, warmer water is more prone to emit methane, while wildfires and biomass burning consume the hydroxyl radicals that are necessary for removing methane from the atmosphere (Cheng and Redfern 2022). Nitrous oxide is another potent GHG that originates from agricultural fertilizers, wastewater, and deforestation, as well as from fossil fuel use and industries (Tian et al. 2020). It remains in the atmosphere for 109 years, and its warming potential is 273 times than carbon dioxide over a 100 years period. Atmospheric concentrations of both methane and nitrous oxide have grown beyond expectations in recent years, underscoring the urgency of addressing these emissions. In addition, vast amounts of GHGs are stored latently in soil, biomass, and oceans. These stores can be many times larger than the total fossil fuel reserves on Earth and need to remain undisturbed (Figure 2.3).

For resilience and sustainability, freshwater thus plays (sometimes simultaneously) three different roles: a) a **provider of resilience**; i.e., by maintaining system functions, such as the upholding of habitats that continue to store and sequester land carbon; b) a **victim of change**; i.e., as freshwater flows and stocks are modified by human pressures or modifications such as forestation impacts on river flows; and c) a **driver of change**; i.e., as freshwater change generates impacts, such as drought impacts on fire risks (Falkenmark et al. 2019; Rockström et al. 2014).

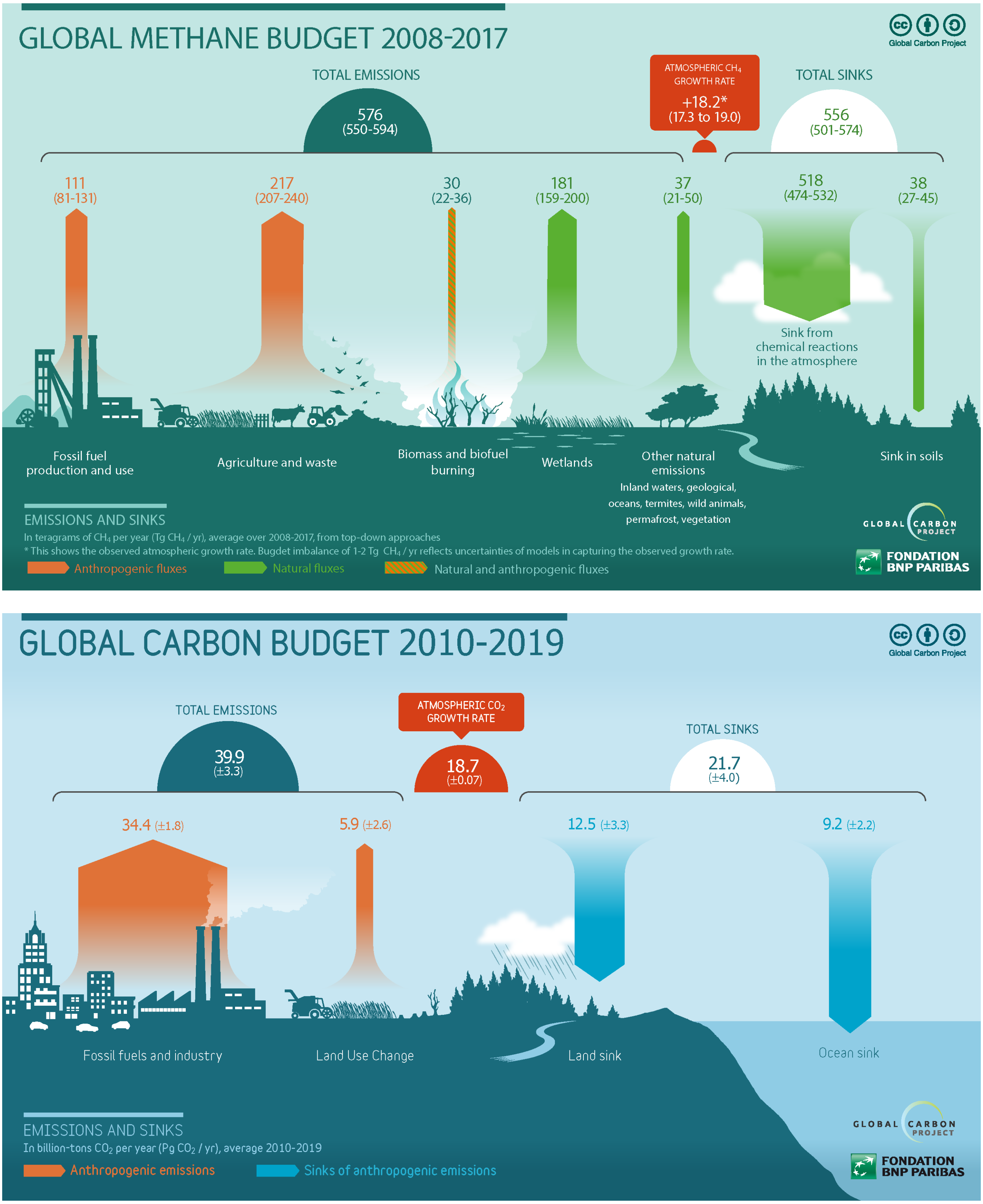

Figure 2.3. Global carbon and methane budgets: a) Global methane budget, average 2008–2017. Source: Saunois et al. (2020); b) Global carbon budget, 2021. Source: Friedlingstein et al. (2022). Graphics courtesy of the Global Carbon Atlas (www.globalcarbonatlas.org).

Together, the four Earth system functions and the three roles of freshwater are dynamically and inseparably interlinked and shape the ways mitigation measures depend on and impact freshwater and freshwater-dependent ecosystems. Thus, water cannot be taken out of the equation when saving the functioning of the Earth system from climate change.

2.3 Introduction to key water-related mitigation measures

To prevent further damage and reach the goal of the Paris Agreement to limit global warming to 1.5 to 2°C above pre-industrial levels (1850–1900), all sectors urgently need to lower their emissions following a holistic approach. The window of opportunity to achieve the Paris Agreement is closing, as global carbon dioxide (CO_2) emissions now need to peak before 2025 and reach net zero by the early 2050s (IPCC 2022b). Otherwise, climate risks to societies and ecosystems will increase with global warming and reach dangerous levels, resulting in water and food insecurity, extreme weather events (such as heatwaves, droughts, fires, storms, flooding), ecosystem regime shifts,[3] sea-level rise, ill health, economic damage, and more (IPCC 2022a). And yet, we are not on track. Current anthropogenic-driven climate change has already led to a 1.1°C warmer world, and without deep reductions in GHG emissions, global warming of 1.5°C and 2°C will be exceeded during the 21st century (IPCC 2022b).

Scenarios that comply with the Paris Agreement temperature target rely on the Earth system's capability to continue to store carbon, which may be compromised due to adverse climate change impacts (Figure 2.4). Various scenarios and pathways to rapid decarbonization exist and include both considerable reductions in human GHG emissions and removal of CO_2[4] from the atmosphere by locking it in human and biosphere carbon sinks. Human carbon emissions are caused by combustion of fossil fuels (coal, oil, and gas) and land-use change, whereas biosphere carbon sinks include uptake of carbon in soils, and dead and living matter in terrestrial and oceanic systems. Human carbon sinks are needed to achieve net zero and refer to uptake and durable storage of carbon in land, oceans, geological formations, or products. Human carbon sink methods that rely on land and freshwater systems include afforestation, reforestation, improved forest

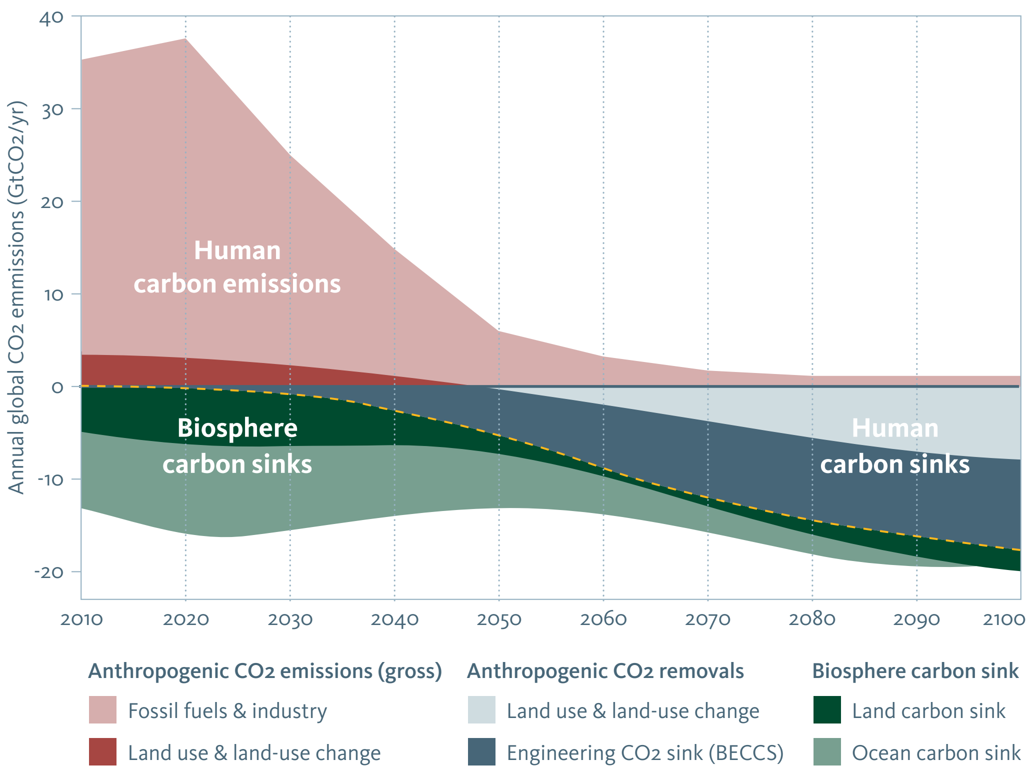

Figure 2.4. Sustainable future scenarios, in which Paris Agreement targets are achieved, typically involve mitigation measures that: a) rapidly cut human GHG emissions; b) maintain the biosphere's capacity to store and sequester carbon; and c) remove carbon from the atmosphere. The figure illustrates a roadmap for rapid decarbonization that meets the Paris Agreement by bending the carbon emissions curve by 2020, reaching net zero by 2050 and increasing human carbon removal such as carbon sinks from BECCS. Source: re-printed with permission from Folke et al. (2021); modified after Rockström et al. (2017).

3. Large, abrupt, and persistent changes in the structure and function of ecosystems, which are difficult or impossible to reverse.
4. Removal of methane and nitrous oxides are being hypothetically explored in the scientific literature (Lackner 2020; Jackson et al. 2019).

management, agroforestry, soil carbon sequestration, peatland restoration, and 'blue carbon'[5] management. Many of these human carbon sinks can contribute simultaneously towards sustainability in several aspects. Others, however, such as afforestation and bioenergy with carbon capture and storage (BECCS),[6] may imply undesirable risks and trade-offs with regards to water and food security, biodiversity, and social systems that need to be considered (IPCC 2022b; also see Chapters 6 and 7).

This report focuses on both human and biosphere mitigation measures that interact considerably with the freshwater cycle and freshwater-based ecosystem processes. This includes mitigation in the WASH sector, freshwater ecosystems (such as wetlands, rivers, etc.), terrestrial systems (such as forest/forestry, grassland/rangeland, and croplands), and the energy production sector, which all crucially depend on or impact water. Mitigation measures with high mitigation potential are also found in the transport, waste, industrial, and buildings sectors, but are not addressed here since the interdependencies with the freshwater cycle are mostly indirect. All in all, the water-interdependent mitigation measures addressed in this report encompass most of the total mitigation potential (Figure 2.5).

2.4 Towards net zero: Why key climate mitigation measures depend on and impact freshwater

The freshwater cycle has been described as the bloodstream of the biosphere and the Earth system (Ripl 2003), meaning that climate mitigation measures and the water cycle are inseparable from the Earth's climate and biosphere processes. As such, all climate mitigation measures inevitably depend on or impact freshwater cycling. Climate mitigation measures (for the purpose of limiting global temperature rise) intervene in land-based systems, freshwater systems, and technological systems, which all depend on the availability of green and blue water of good quality. Conversely, the failure or success of climate mitigation efforts directly impacts how climate change affects the water cycle as well as the effectiveness of climate mitigation measures.

To start with, absent or insufficient mitigation measures are likely to lead to more severe climate change, and thereby to potential shifts in hydro-climatic regimes (Dai 2021; Destouni et al. 2012; Piemontese et al. 2019) and abrupt changes in the water cycle (Huntington

Early morning evaporation from a freshwater lake, Sweden. Source: Shutterstock.

5. Carbon storage in coastal and marine ecosystems, i.e., mangroves, tidal marshes, and seagrasses.
6. BECCS is a negative emission technology that involves harvesting biomass for energy production and storing carbon in geologic formations or land (see Chapter 7).

Many options available now in all sectors are estimated to offer substantial potential to reduce net emissions by 2030. Relative potentials and costs will vary across countries and in the longer term compared to 2030.

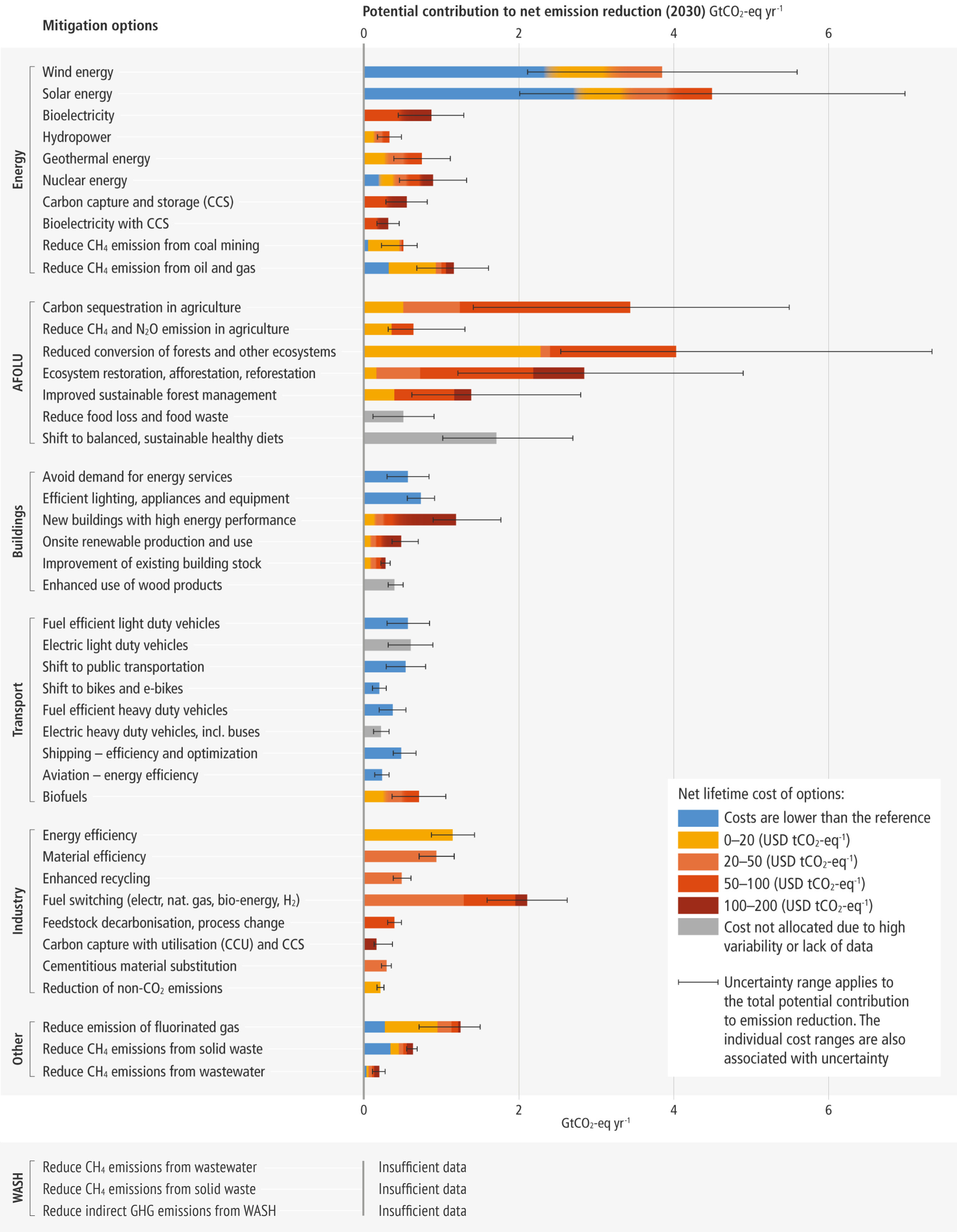

Figure 2.5. Mitigation measures across sectors and their mitigation potential to reduce net emissions by 2030. Source: IPCC Sixth Assessment Report, https://www.ipcc.ch/report/ar6/wg3/figures/summary-for-policymakers/figure-spm-7/. The WASH section is based on the findings in Chapter 4 of this report.

2006; Zhang et al. 2019). Many regions are swiftly becoming either wetter or drier, which alters ecological and biogeochemical functions and processes. The shifting hydroclimate and water cycle intensification lead to increasingly frequent and severe water-related extremes, including fires, droughts, heatwaves, storms, extreme precipitation events, and subsequent risks of erosion, flooding, and landslides (IPCC 2022b). With increasing frequency of extreme events, individual risks are more prone to aggregate into compound risks (which result from multiple simultaneous and interacting climate and non-climate risks), such as food insecurity aggravated by concurrent droughts, heatwaves, and conflicts (IPCC 2022c; Zscheischler et al. 2018).

The speed of change can exceed the capacity of ecosystems to adapt and compromises their capacity to retain their functions and structures under external disturbances. Limits to adaptation are already being felt and will increase with further warming (IPCC 2022c). Human impacts on climate, land, and water together increase the risk of abrupt ecological and social-ecological change that are difficult or impossible to reverse (i.e., tipping points, see Figure 2.6). Such regional water risks arising primarily from global change include glacier melt, sea-level rise, salt-water intrusion, and drastic rainfall regime change. Mismanagement of land and water further contribute to the risk of gradual collapse or irreversible tipping. Examples include land degradation (e.g., loss of infiltration capacity further contributes to drying soils), salinization (e.g., if agricultural land is irrigated with salty water), Amazon forest dieback (e.g., forest loss leads to reduced evapotranspiration and regional precipitation), and groundwater depletion and surface water depletion (e.g., river water is consumed before reaching the ocean). This means that the necessary large-scale and rapid roll-out of climate change mitigation measures, at the same time, must avoid contributing to mismanagement and resilience loss in land-based and freshwater systems.

Unmitigated climate change impacts on soil moisture will compromise the effectiveness of many land-based mitigation measures. Mitigation measures dependent on the ability of ecosystems to store and sequester carbon are directly impacted by changes in green water fluxes and stores. For example, climate change induced decreases in soil moisture often limit the capability of plants to grow and sequester carbon both below and above ground (Green et al. 2019; Samaniego et al. 2018). As plants wither and wetlands dry up, they revert from being a carbon sink to become a carbon source. Instead of absorbing CO_2 emissions, they release stored GHGs to the atmosphere, accelerating climate change. This is already happening in the tropical rainforests (Hubau et al. 2020). There are concerns that a global tipping point of carbon sink-to-source reversal will occur by the middle of this century under severe climate change (RCP8.5)[7] (Green et al., 2019). An increasing concentration of CO_2 in the atmosphere initially enables more water-efficient photosynthesis (i.e., CO_2 fertilization), thus bolstering vegetation growth and increasing carbon uptake. However, eventually, the CO_2 fertilization effect will saturate (Green et al. 2019) due to such limits as the maximum ecosystem photosynthesis rate or because of water limitations, nutrient limitations, and other constraining factors (Wieder et al. 2015). Increased wetting caused by thawing permafrost can cause increased CO_2 and methane release (Schaphoff et al. 2013; Turetsky et al. 2020). The success of mitigation measures that are aimed at the protection and restoration of terrestrial systems for carbon storage and uptake thus depend on the future severity of (incompletely mitigated) climate change.

Similarly, unmitigated climate change impacts on blue water can be expected to lower the mitigation potential of measures aimed at the protection and restoration of aquatic systems. For example, regional declines in groundwater recharge (Portmann et al. 2013) may limit water availability for delivering groundwater-dependent mitigation measures such as ecosystem restoration, reforestation, electricity production, and mining for minerals, which are needed to produce renewable infrastructure. Increased flooding risks, associated with precipitation extremes and glacial melt under climate change (Merz et al. 2021), present further risks to downstream aquatic ecosystems, hydropower dams, and other water infrastructure. Climate change increases the fraction of the world's population exposed to water scarcity (Gerten et al. 2013; Heinke et al. 2019) (Figure 2.7), which will require resilient and efficient water infrastructures for supplying water to households and industries. The capacity of coastal and marine systems to sequester and store carbon can be further compromised by rising sea level as well as increasing incidence of extreme events such as marine heatwaves and storms (Macreadie et al. 2019).

7. This high-emissions Intergovernmental Panel on Climate Change scenario is frequently referred to as 'business as usual', suggesting that is a likely outcome if society does not make concerted efforts to cut GHG emissions.

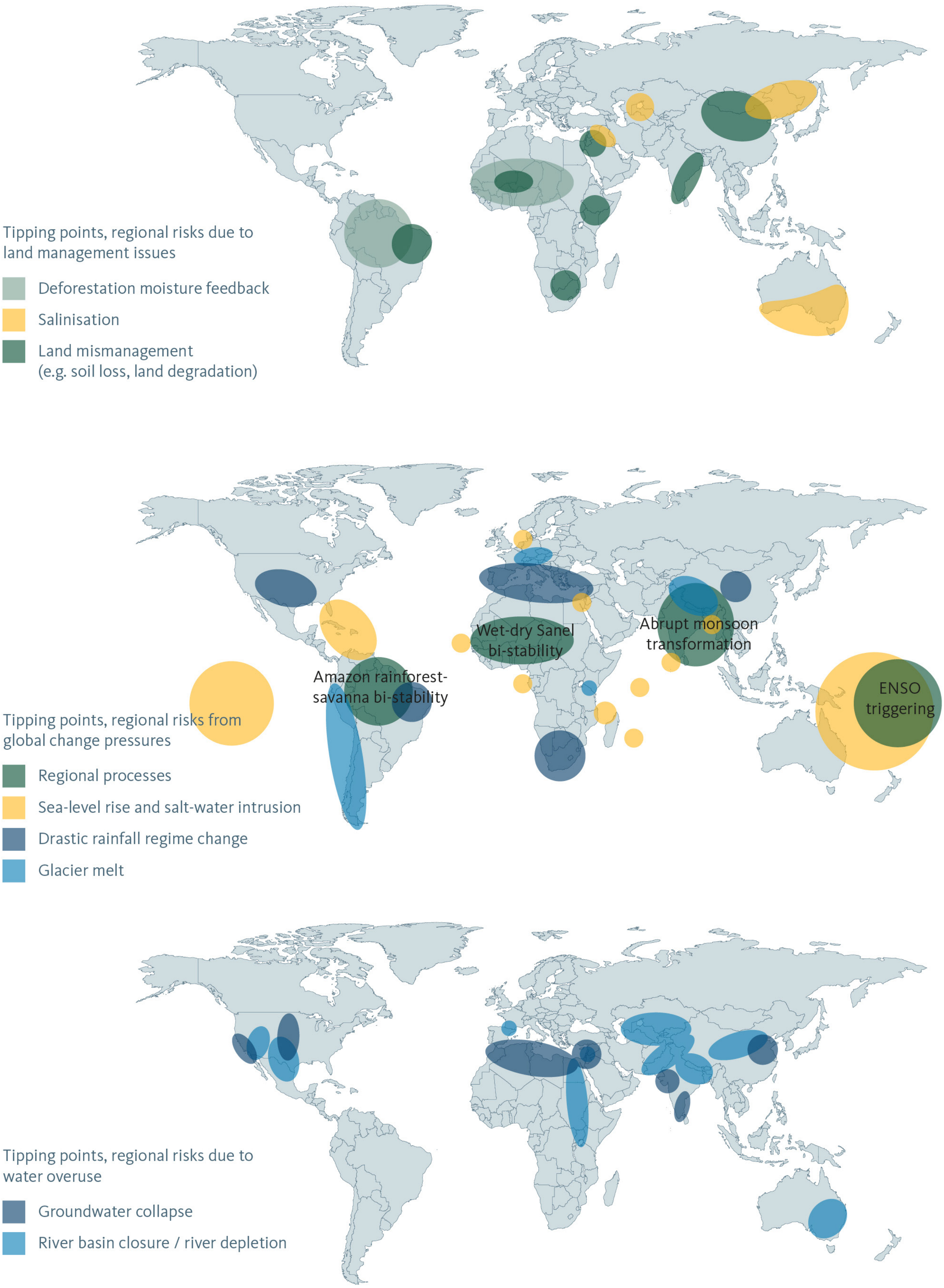

Figure 2.6. Water-related tipping points in the Earth system. In addition, permafrost thawing associated with local abrupt shifts can be expected under climate change. Source: Rockström et al. (2014); Schaphoff et al. (2013); Turetsky et al. (2020).

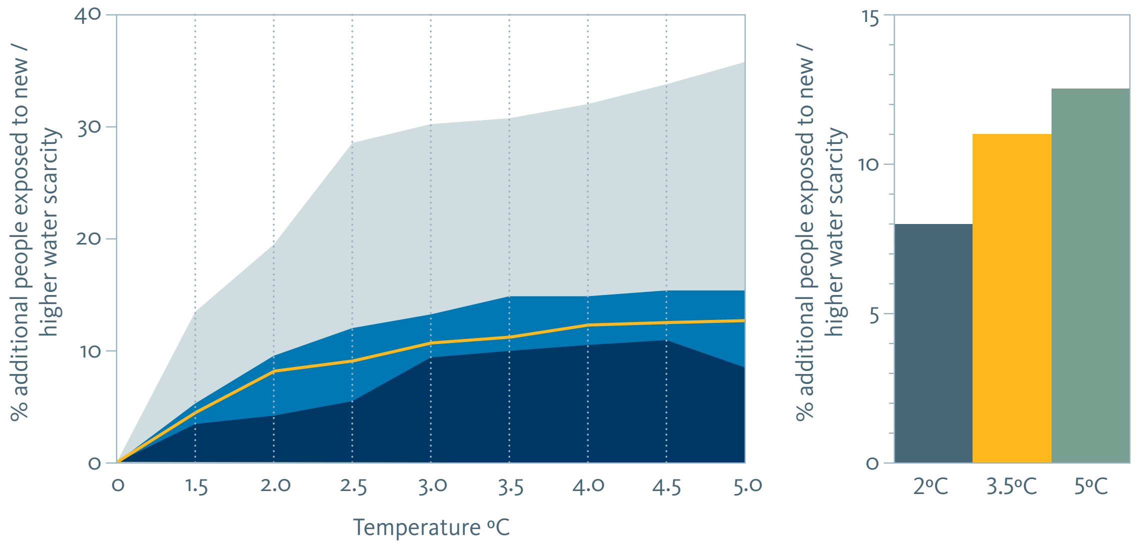

Figure 2.7. With every degree of global warming, more people will be exposed to water scarcity. Source: Heinke et al. (2019).

A rapid rollout of mitigation measures is, however, not risk free for water and needs to be carried out carefully to prevent unintentional harm. The way that mitigation measures directly affect and depend on freshwater vary in land-based ecological and production systems, freshwater ecological and production systems, and technological systems (Figure 2.8).

1. Mitigation measures in land-based ecological and production systems refer to climate actions in forests, agriculture, grasslands, and rangelands. They aim to lock carbon in those land systems instead of releasing it into the atmosphere by increasing land carbon sequestration and maintaining land carbon stocks. At the same time, most interventions on land lead to changes in vegetation types and management methods, thereby resulting in changes in surface reflection and evaporation, which affect local temperatures. Increased carbon sequestration can be achieved through expanded above- and below-ground biomass, such as by reforestation, afforestation, and forest management. However, land-based ecosystems need to remain intact to harness their mitigation potential. Ecosystem health in turn depends on water security; carbon stocks in the soils and biomass of ecosystems need to be maintained to have a climate mitigating effect in the long term. Yet forests and grasslands cannot thrive without water. In addition, the longevity of these living carbon stocks is subject to extreme events and climate change. For example, drought may facilitate wildfires, which cause vegetation mortality and prevent growth. Hence, it directly obstructs carbon sequestration in land systems and even releases land carbon stocks to the atmosphere (Wen et al. 2020). Changes in the carbon balance, however, are only one of many biophysical aspects of mitigation interventions in land systems. An assessment of the overall effect on surface temperatures needs to also include effects of land conversion/management on surface albedo[8] and non-radiative forcing.[9] This refers to local cooling through evaporation and turbulence increase. For example, conversion of grassland to coniferous tree cover in boreal areas may lead to an increase in the Earth's energy balance (Bala et al., 2007; Bonan, 2008; Swann et al., 2010), but simultaneously lower local temperatures (Bright et al. 2017), which can be very important for preventing fires, vegetation mortality, and species loss.

2. Freshwater ecological and production systems encompass wetlands, lakes, rivers, reservoirs, groundwater, and freshwater-dependent coastal and marine systems. They are dependent on water security and critically relevant to mitigation measures by, among others, storing and absorbing GHGs (CO_2, methane, and nitrous oxide, see Chapter 5) and enabling

8. Albedo refers to the fraction of radiation that is reflected by a surface. Dense vegetation types, such as forests, typically have a lower albedo than grasslands, croplands, and deserts.
9. Non-radiative forcing refers to a change to the partitioning and distribution of energy that can affect temperature, without affecting the overall radiative balance of the Earth. Non-radiative forcing includes changes in evaporation (i.e., heat fluxes that cause evaporation do not contribute to surface temperature change) and surface roughness (i.e., land with high vegetation cover has higher surface roughness than barren landscapes). For example, tropical deforestation increases temperature through both types of non-radiative forcing: non-forests have lower surface roughness, thereby lower atmospheric turbulence, which prevents warm air from leaving the surface area; and non-forests also evaporate less, thereby lower evaporative cooling effects, which increases surface temperatures (Davin and de Noblet-Ducoudré 2010).

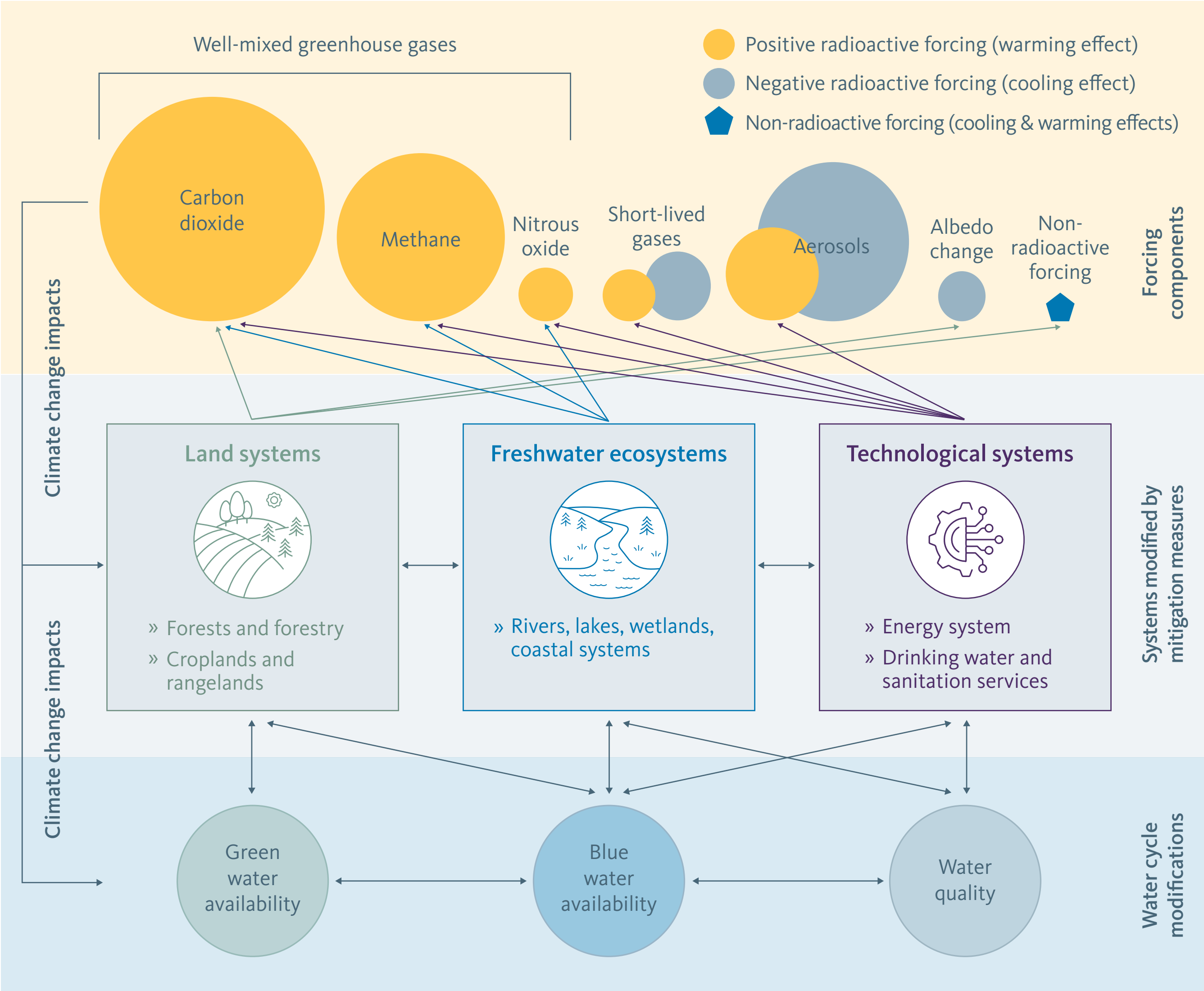

Figure 2.8. Overview of the key relationships between water-related mitigation measures and climate forcings. The size of the circles represents rough approximates of the magnitude of the forcing changes over the period 1750–2011 and includes all changes (i.e., not only from the terrestrial and aquatic systems or fossil energy sources). Source: Stockholm International Water Institute.

renewable and low-emission energy generation (Chapter 7). The densest and most long-term carbon stocks are found in natural aquatic systems. However, they are at risk of reverting from net sinks to net sources as a result of drainage, pollution, global warming, and other human pressures. For example, if a peatland ecosystem is destroyed or degraded, the carbon it stores is released into the atmosphere. This is particularly concerning because peatlands store twice as much carbon as the world's forests (see Chapter 5) and peatland degradation currently represents up to 5 per cent of human emissions (HLPW 2018). In many regions, the impact of drying and wetting on climate change further depends on the balance between aerobic emissions of CO_2 (long-lived in the atmosphere) and anaerobic emissions of methane (~30 times larger warming potential over 100 years). Yet, for example, to replace fossil-fuel-based energy sources, future zero emission scenarios typically assume dramatic expansions of hydropower (e.g., 60 per cent increase in the next 30 years) (IRENA 2020) with potentially large impacts on fish migration, ecosystem health, and livelihoods (see Chapter 7). Thus, the overall potential of aquatic systems to contribute to climate change mitigation depends on safeguarding the capacity of these systems to act as persistent GHG sinks, while planning the provision of renewable energy.

3. Mitigation measures in freshwater-related technological systems addressed in this report primarily concern the WASH sector and the energy sector. The WASH sector uses 4 per cent of the global water supply with considerable opportunities for increases in energy efficiency. In addition, reductions can be achieved in the methane and nitrous oxide emissions from water and wastewater treatment, desalination, and water infrastructures (Chapter 4). A rapid transition of global energy production from fossil to renewable and low-emission energy sources is fundamentally interdependent on freshwater. Among others, hydropower and bioenergy are the renewable energy sources most directly dependent on freshwater for generating energy directly by moving turbines and in biomass production respectively. Thermal electricity generation from nuclear, concentrated solar, and geothermal energy can require large volumes of water for their operations (cleaning and cooling) and discharged water can impact temperature and environmental health in freshwater systems. Taken together, decarbonization of the energy sector requires water security due to considerable water use for cooling, cleaning, biomass production, and the energy generation itself (Chapter 7).

2.5 Carbon smart and water wise: How to achieve sustainable mitigation action

We need to prevent uninformed water mitigation planning from threatening freshwater resources and ecosystems to safeguard mitigation potentials. The circularity between mitigation measures and freshwater systems must be acknowledged and taken into account during planning.

Mitigation measures that modify freshwater and freshwater-dependent systems can similarly have indirect impacts on subsequent mitigation potential, creating both risks and win-win situations. Water risks can be expected, for example, with hydropower, which can help reduce reliance on fossil fuel energy sources and reduce emissions, but might simultaneously negatively impact the ecological functioning and carbon sequestration capacity of local aquatic systems (Moran et al. 2018). Moreover, irrigation-dependent plantations for measures such as BECCS (Stenzel et al. 2021) could unintentionally deplete local water resources (see Chapter 7), with detriments to the original ecological and carbon sequestering functioning of the impacted ecosystems. Win-wins are, fortunately, also numerous. For instance, better wastewater treatment reduces the GHG emissions from untreated wastewater, improves surface water and groundwater quality, and provides renewable energy through biogas (Macreadie et al. 2019). Restoration of forests and wetlands also has a high potential to serve social, ecological, and climate benefits all at once (Di Sacco et al. 2021). In many cases, the risks and win-wins are complex and depend on both context and the water-wise execution/operation of the planned and proposed mitigation measures.

Overall, freshwater is crucial to the functioning of the entire Earth system and the fundamental underpinning of societies, livelihoods, and the world's economy (Daily 1997; Dasgupta 2021). Mitigation measures in the WASH sector, energy sector, and involving terrestrial and aquatic systems inevitably depend on and impact freshwater systems. Freshwater availability impacts ecosystems' ability to absorb and store carbon, methane, and nitrous oxide; freshwater is used for energy generation and in technological processes within renewable and low-emission energy production. Climate change, however, is already negatively impacting freshwater availability and quality. Slow or insufficient climate mitigation will lead to extreme events, such as droughts, fires, and floods, as well as to hydroclimatic shifts and abrupt changes in ecosystems that will disrupt the freshwater functions that critically support and enable a large range of nature-based and technological mitigation measures.

Therefore, mitigation measures need to be rolled out rapidly while at the same time restoring and limiting negative impacts on freshwater resources and freshwater-dependent systems. Time is a critical factor, as rapid implementation of mitigation measures that limit climate change is also likely to benefit the effectiveness of freshwater-dependent mitigation measures. It is critical to restore and limit negative impacts on ecosystem functioning because ecosystems' capacity to store and sequester carbon is intimately reliant on ecosystem health. The precarious conditions of the Earth system, with transgressions in six out of nine planetary boundaries – including that of freshwater change (Wang-Erlandsson et al., 2022) – further motivates ecosystem-friendly mitigation measures and stresses the need for caution concerning mitigation measures that carry freshwater risks.

Rapid and water-smart mitigation measures are needed to harness the potential of freshwater ecosystems and avoid jeopardizing health, water, food, and energy security, which form the foundations of societies.

2.6 References

Bala, G., Caldeira, K., Wickett, M. et al. (2007) Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academy of Sciences*, 104 (16): 6550–6555

Bonan, G. B. (2008) Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science* 320 (5882): 1444–1449

Bright, R. M., Davin, E., O'Halloran, T. et al. (2017) Local Temperature Response to Land Cover and Management Change Driven by Non-Radiative Processes. *Nature Climate Change*, 7: 296–302

Cheng, C-H. & Redfern, S. A. T. (2022) Impact of Interannual and Multidecadal Trends on Methane-Climate Feedbacks and Sensitivity. *Nature Communications* 13 (1): 3592

Dai, A. (2021) Hydroclimatic Trends during 1950–2018 over Global Land. *Climate Dynamics* 56 (11): 4027–49

Daily, G. C. (1997) *Nature's Services: Societal Dependence On Natural Ecosystems*. Island Press: Washington D. C.

Dasgupta, P. (2021) *The Economics of Biodiversity: The Dasgupta Review: Full Report.* HM Treasury: London

Davin, E. L. & de Noblet-Ducoudré, N. (2010) Climatic Impact of Global-Scale Deforestation: Radiative versus Nonradiative Processes. *Journal of Climate* 23 (1): 97-112

Destouni, G., Jaramillo, F. & Prieto, C. (2012) Hydroclimatic Shifts Driven by Human Water Use for Food and Energy Production. *Nature Climate Change* 3 (3): 213–17

Di Sacco, A., Hardwick, K. A., Blakesley, D. et al. (2021) Ten Golden Rules for Reforestation to Optimize Carbon Sequestration, Biodiversity Recovery and Livelihood Benefits. *Global Change Biology* 27 (7): 1328–48

Douville, H., K., Raghavan, J., Renwick, R. P. et al. (2021) Water Cycle Changes. In *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., Zhai, P., Pirani, A. et al. (eds) Cambridge University Press: Cambridge, UK and New York, NY, USA

van der Ent, R. J., Savenije, H. H. G., Schaefli, B., & Steele-Dunne S. C. (2010) Origin and Fate of Atmospheric Moisture over Continents. *Water Resources Research* 46 (9): 1-12

Falkenmark, M. & J. Rockström. (2006) The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management. *Journal of Water Resources Planning and Management* 132 (3): 129–32

Falkenmark, M., Wang-Erlandsson, L. & Rockström, J. (2019) Understanding of Water Resilience in the Anthropocene. *Journal of Hydrology* X (2): 100009

Folke, C., Polasky, S., Rockström, J. et al. (2021) Our future in the Anthropocene biosphere. *Ambio* 50: 834–869

Friedlingstein, P. et al. (2022) Global Carbon Budget 2021. *Earth Syst. Sci. Data* 14 (4): 1917–2005

Gerten, D., Lucht, W., Ostberg, S. et al. (2013) Asynchronous Exposure to Global Warming: Freshwater Resources and Terrestrial Ecosystems. *Environmental Research Letters* 8 (3): 1-12

GIZ, adelphi, & PIK. (2020) *Stop Floating, Start Swimming: Water and Climate Change – Interlinkages and Prospects for Future Action*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Gleeson, Wang-Erlandsson, Zipper, Porkka, Jaramillo, Gerten, Fetzer, et al. 2020. "The Water Planetary Boundary: Interrogation and Revision." *One Earth* 2 (3): 223–34

Green, J. K., Seneviratne, S., I., Berg, A. M. et al. (2019) Large Influence of Soil Moisture on Long-Term Terrestrial Carbon Uptake. *Nature* 565 (7740): 476–79

Heinke, J., Müller, C., Lannerstad, M. et al. (2019) Freshwater Resources under Success and Failure of the Paris Climate Agreement. *Earth System Dynamics* 10 (2): 205–17

HLPW. (2018) *Every Drop Counts. An Agenda for Water Action*

Hubau, W., Lewis, S. L., Phillips, O. L. et al. (2020) Asynchronous Carbon Sink Saturation in African and Amazonian Tropical Forests. *Nature* 579 (7797): 80–87

Huntington, T. G. (2006) Evidence for Intensification of the Global Water Cycle: Review and Synthesis. *Journal of Hydrology* 319 (1): 83–95

IRENA. (2020) *Global Renewables Outlook: Energy Transformation 2050*. International Renewable Energy Agency

IPCC. (2022a) *Climate Change 2022: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Pörtner, H-O., Roberts, D. C., Tignor, M. et al. (eds) Cambridge University Press: Cambridge, UK and New York, NY, USA

———. (2022b) *Climate Change 2022: Mitigation of Climate Change*. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change." Shukla, P. R., Skea, J., Slade, R., et al. (eds) Cambridge University Press: Cambridge University Press: Cambridge, UK and New York, NY, USA

———. (2022c) 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* Pörtner, H-O., Roberts, D. C., Tignor, M. et al. (eds) Cambridge University Press: Cambridge, UK and New York, NY, USA

Jackson, R. B., Solomon, E. I., Canadell, J. G. et al. (2019) Methane Removal and Atmospheric Restoration. *Nature Sustainability* 2 (6): 436–38

Keys, P. W., van der Ent, R. J., Gordon, L. J. et al. (2012) Analyzing Precipitationsheds to Understand the Vulnerability of Rainfall Dependent Regions. *Biogeosciences* 9 (2): 733–46

Keys, P. W., Wang-Erlandsson, L. & Gordon, L. J. (2016) Revealing Invisible Water: Moisture Recycling as an Ecosystem Service. *PloS One* 11 (3): e0151993

Keys, P. W., Wang-Erlandsson, L., Gordon, L. J., et al. (2017) Approaching Moisture Recycling Governance. *Global Environmental Change* 45: 15-23

Lackner, K. S. 2020. Practical Constraints on Atmospheric Methane Removal. *Nature Sustainability* 3 (5): 357–357

Macreadie, P. I., Anton, A., Raven, J. A. et al. (2019) The Future of Blue Carbon Science. *Nature Communications* 10 (1): 3998

Merz, B., Blöschl, G., Vorogushyn, S. et al. (2021) Causes, Impacts and Patterns of Disastrous River Floods. *Nature Reviews Earth & Environment* 2 (9): 592–609

Moran, E. F., Lopez, M. C., Moore, N. et al. (2018) Sustainable Hydropower in the 21st Century. *Proceedings of the National Academy of Sciences of the United States of America* 115 (47): 11891–98

Piemontese, L., Fetzer, I., Rockström, J. & Jaramillo, F. (2019) Future Hydroclimatic Impacts on Africa: Beyond the Paris Agreement. *Earth's Future* 7 (7): 748–61

Portmann, F. T., Döll, P., Eisner, S. & Flörke, M. (2013) Impact of Climate Change on Renewable Groundwater Resources: Assessing the Benefits of Avoided Greenhouse Gas Emissions Using Selected CMIP5 Climate Projections. *Environmental Research Letters: ERL [Web Site]* 8 (2): 024023

Ripl, W. (2003) Water: The Bloodstream of the Biosphere. Philosophical Transactions of the Royal Society of London. Series B, *Biological Sciences* 358 (1440): 1921–34

Rockström, J., et al. (2017) A roadmap for rapid decarbonization. *Science* 355 (6331): 1269-1271

Rockström, J., Karlberg, L., Wani, S. P. et al. (2010) Managing Water in Rainfed agriculture—The Need for a Paradigm Shift. *Agricultural Water Management* 97 (4): 543-550

Rockström, J., Falkenmark, M., Folke, C., Lannerstad, M., and Barron, J. 2014. *Water Resilience for Human Prosperity*. Cambridge University Press: Cambridge UK

Russo, S., Sillmann, J., & Sterl, A. (2017) Humid Heat Waves at Different Warming Levels. *Scientific Reports* 7 (1): 7477

Samaniego, L., S. Kumar, T. R. N., Rakovec, W. O. et al. (2018) Anthropogenic Warming Exacerbates European Soil Moisture Droughts. *Nature Climate Change* 8 (5): 421–26

Saunois, M., Stavert, A. R., Poulter, B. et al. (2020) The Global Methane Budget 2000–2017. *Earth System Science Data* 12 (3): 1561–1623

Schaphoff, S., Heyder, U., Ostberg, S. et al. (2013) Contribution of Permafrost Soils to the Global Carbon Budget. *Environmental Research Letters* 8 (1): 014026

Stenzel, F., Greve, P., Lucht, W. et al. (2021) Irrigation of Biomass Plantations May Globally Increase Water Stress More than Climate Change. *Nature Communications* 12 (1): 1512

Swan et al. (2010) Changes in Arctic vegetation amplify high-latitude warming through the greenhouse effect. *PNAS.* 107 (4) 1295-1300

Tian, H., Xu, R., Canadell, J. G. et al. (2020) A Comprehensive Quantification of Global Nitrous Oxide Sources and Sinks. *Nature* 586 (7828): 248–56

Turetsky, M. R., Abbott, B. W., Jones, M. C. et al. (2020) Carbon Release through Abrupt Permafrost Thaw. *Nature Geoscience* 13 (2): 138–43

Wang-Erlandsson, L., Tobian, A., van der Ent, R.J. et al. A planetary boundary for green water. *Nat Rev Earth Environ* 3, 380–392 (2022).

Wen, H., Perdrial, J., Abbott, B. W. et al. (2020) Temperature Controls Production but Hydrology Regulates Export of Dissolved Organic Carbon at the Catchment Scale. *Hydrol. Earth Syst. Sci.* 24 (2): 945–966

Wieder, W. R., Cleveland, C. C., Smith, W. K., & Todd-Brown, K. (2015) Future Productivity and Carbon Storage Limited by Terrestrial Nutrient Availability. *Nature Geoscience* 8 (6): 441–44

te Wierik, S. A., Gupta, J., Cammeraat, E. L. H. & Artzy-Randrup, Y. A. (2020) The Need for Green and Atmospheric Water Governance. *Wiley Interdisciplinary Reviews: Water* 7 (2): e1406

Zhang, W., Zhou, T., Zhang, L. & Zou, L. (2019) Future Intensification of the Water Cycle with an Enhanced Annual Cycle over Global Land Monsoon Regions. *Journal of Climate* 32 (17): 5437–52

Zscheischler, J., Westra, S., van den Hurk, B. J. J. M. et al. (2018) Future Climate Risk from Compound Events. *Nature Climate Change* 8 (6): 469–77