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Hydrological limits to carbon capture and storage

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Carbon capture and storage (CCS) is a strategy to mitigate climate change by limiting CO_2 emissions from point sources such as coal-fired power plants (CFPPs). Although decision-makers are seeking to implement policies regarding CCS, the consequences of this technology on water scarcity have not been fully assessed. Here we simulate the impacts on water resources that would result from retrofitting global CFPPs with four different CCS technologies. We find that 43% of the global CFPP capacity experiences water scarcity for at least one month per year and 32% experiences scarcity for five or more months per year. Although retrofitting CFPPs with CCS would not greatly exacerbate water scarcity, we show that certain geographies lack sufficient water resources to meet the additional water demands of CCS technologies. For CFPPs located in these water-scarce areas, the trade-offs between the climate change mitigation benefits and the increased pressure on water resources of CCS should be weighed. We conclude that CCS should be preferentially deployed at those facilities least impacted by water scarcity.

Globally, coal-fired power plants (CFPPs) account for 38% of electricity generation[1] and 19% of total CO_2 emissions[2]. Coal-fired power generation is also a primary source of toxic airborne emissions globally[3]. Despite the growing reliance on renewable energy and recent policy efforts aimed at reducing the use of coal[4], the global dependence on coal for power generation is the same as it was 20 years ago[1]. Since the turn of the twenty-first century, population growth, increasing affluence and industrialization in developing countries have caused an unprecedented growth in coal consumption (+57%)[1], leading to a boom in the construction of CFPPs[2]. Given that each new coal plant is at least a US$1 billion investment with a 30- to 50-year lifetime[5], currently operating CFPPs commit the energy sector to emissions above levels compatible with a 1.5–2.0 °C limit on global temperature rise[6] and commit freshwater consumption to levels that potentially compete with natural ecosystems and other human uses[7–21]. These commitments necessitate paying increasing attention to global water scarcity[22] in the context of humankind's ability to meet its burgeoning food and energy needs[23].

A successful solution towards mitigating climate change will curtail CO_2 emissions and minimize unnecessary use of water resources in managed energy systems with minimum costs. Although renewable energy and other technologies that replace coal are necessary and increasingly viable, a portfolio of climate solutions must account for the existing assets and committed billion-dollar investments in coal[24,25]. Postcombustion carbon capture and storage (CCS) is a preferred, economically viable technology to reduce CFPP carbon emissions because it can be retrofitted to existing power plants without decommissioning them[26]. So far, however, a global assessment of the potential impacts of CCS on water resources—should existing CFPPs worldwide be retrofitted with CCS technologies—is missing. As we continue to evaluate the cost-effectiveness of different climate change mitigation technologies, the assessment of potential water limits to CCS can provide relevant and necessary insights.

We consider four prominent CCS technologies that can be deployed to retrofit CFPPs: absorption with amine solvents, membrane separation, and adsorption into solid sorbents by either pressure swing adsorption (PSA) or temperature swing adsorption (TSA) processes (Box 1). Whereas amine-based absorption is proven and commercially available, membrane-based and adsorption-based CCS systems are at lower stages of development[27]. All of these CO_2 capture technologies are energy-intensive processes[28] that would impose parasitic power demands on existing CFPPs and thus decrease their efficiencies[27]. The additional power generation required for CCS would result in additional water consumption by the CFPP cooling process[29]. Moreover, in most cases, additional water is required as an integral part of the carbon capture processes[30]. Recent work has assessed that a post-combustion amine absorption process would nearly double a CFPP's water combustion intensity (Box 1), decrease net plant efficiency from 38% to 26% and increase the levellized cost of electricity by 75% (ref. [31]).

Previous research has simulated water risks of power generation with CCS in the United States[32–35], Europe[36] and the United Kingdom[37]. These studies focused on regional-scale analyses of water requirements from the absorption process without considering other CCS technologies, however, and did not utilize a monthly hydrological model to quantify potential impacts on water resources. These studies fall short of elucidating whether CCS might induce or exacerbate water scarcity at specified times of the year, and what the different water intensity impacts are for the various CCS technologies. A limited hydrological understanding of the potential impacts of CCS adds uncertainties to the environmental consequences of the implementation of CCS worldwide.

Herein we present a global hydrological analysis of the potential impacts on water resources that would result from retrofitting large (>100 MW gross capacity) CFPPs with four types of CCS system. This analysis begins with a monthly, regional assessment of water scarcity experienced by current CFPPs. We assess the monthly water withdrawal and consumption for each CFPP using the Integrated Environmental Control Model (IECM version 11.2)[38] and analyse the exposure of each plant to water scarcity. A comprehensive assessment of water withdrawal, consumption and scarcity facilitates the development of sustainable water management practices and sheds light on the regional hydrological impacts of CCS. Our study improves our understanding of the water requirements of CCS and provides relevant insights to mitigate carbon emissions from the electricity and industry sectors while preserving water resources (Box 1).

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Box 1 | Concepts and definitions

Water systems

Water consumption is the volume of water that is used by human activities and returned to the atmosphere as water vapour. Therefore, this water becomes unavailable for short-term reuse within the same watershed.

Water withdrawal is the total volume of water removed from a water body. This water is partly consumed and partly returned to the source or other water bodies, where it is available for future use.

Water consumption intensity ($m^3 MWh^{-1}$) is the volume of water consumed (m^3) per unit of net power produced (MWh). It is a measure of the efficiency of water consumption.

Water withdrawal intensity ($m^3 MWh^{-1}$) is the volume of water withdrawn (m^3) per unit of net power produced (MWh). It is a measure of efficiency of water withdrawal.

Blue water flows are freshwater flows associated with both surface and groundwater runoff.

Environmental flows describe the quantity, timing and quality of water flows required to sustain freshwater ecosystems.

Available water is the water sustainably available for human use. It is calculated as blue water flows minus environmental flows.

Water scarcity refers to the condition of imbalance between freshwater availability and demand. Here we define water scarcity based on whether the ratio between freshwater consumption and available water is >1 (ref. [22]). Water scarcity corresponds to conditions in which the monthly available water resources are less than the total water consumption, and freshwater requirements from coal-fired generation must therefore compete with the water used for domestic needs and irrigation, as well as environmental flow requirements.

Postcombustion CCS technologies

Postcombustion CCS consists of retrofitting existing power plants with CCS units without having to modify the power plant itself. CO_2 is first separated from the flue gas of power plants. Once captured, CO_2 is compressed to its supercritical fluid state and transported and injected into a safe geological formation (Supplementary Fig. 1).

Absorption is a CCS technology based on using a liquid solvent to dissolve (absorb) CO_2 molecules into a liquid solution such as an aqueous amine. The CO_2-enriched liquid solution is pumped to a regenerator where it is heated to liberate a stream of almost pure gaseous CO_2 and the lean solution is circulated back to the absorber (Supplementary Fig. 2).

Membrane separation is a CCS technology that separates CO_2 from flue gas by selective permeation through a membrane material. CO_2 permeates the membrane if its partial pressure is higher on one side of the membrane relative to the other side (Supplementary Fig. 3), which is accomplished by compression and/or vacuum.

Adsorption is a CCS technology based on adsorption of CO_2 molecules onto the surface of a solid material. The CO_2-enriched solid sorbent can be regenerated by low pressure (PSA) or high temperature (TSA). Gaseous CO_2 is liberated and collected and can be compressed for storage; the lean solid sorbent can be reused (Supplementary Figs. 4 and 5).

Current water scarcity without CCS

Global hydrological models are powerful tools to simulate and quantify changes in water availability and consumption. Here we use water scarcity as an indicator of where, in what period of the year and for how long CFPPs without CCS systems are vulnerable to risks of limited water availability. Our hydrological analysis uses a monthly biophysical water balance model that accounts for water consumption for irrigation, domestic needs and coal-fired power generation, as well as for the environmental flows required to maintain the health of aquatic ecosystems. Our water scarcity results are displayed based on the long-term monthly average available water in the 2011–2015 period, although we have also analysed interannual variability in water resources.

We find that 32% (625 GW) of CFPPs exhibit water scarcity for five or more months per year and 43% (830 GW) of the world's CFPPs face regional water scarcity for at least one month per year. Of these 32%, 56% are located in China, 15% in India and 11% in the United States. Other CFPPs facing water scarcity for at least five months per year are located in South Africa (34 GW), Australia (12 GW), Russia (8 GW), Poland (8 GW) and Germany (7 GW).

Figure 1 shows the geographical distribution, water scarcity duration (in months) and cooling technology of CFPPs operating in 2018. CFPPs are typically built adjacent to lakes, rivers or oceans where water availability is abundant. CFPPs that do not face water scarcity year-round are located in the Great Lakes region in the northeastern United States, and in Europe, Russia and southern China. Other CFPPs not affected by water scarcity are located along the coasts where they can use seawater as a cooling medium (we assumed that CFPPs currently cooled with seawater are not affected by water scarcity).

Our analysis of the share of CFPP capacity currently facing water scarcity in different regions of the world and months of the year shows that in China more than 30% of the installed capacity faces water scarcity from March to October (Fig. 2a). In the United States, at least 20% of CFPP capacity faces water scarcity from April to November. A similar picture can be found in Europe, where at least 20% of CFPP capacity faces water scarcity from June to September. More than 40% of India's CFPP capacity faces water scarcity in the dry season (December–June). CFPPs located in other Asian countries are not particularly exposed to water scarcity because of high water availability and their construction along the coast to use seawater as a cooling medium. It is worth noting that for those global CFPPs that use freshwater for cooling, the predominant cooling technologies are wet-cooling towers (60% of total capacity), followed by once-through systems (35%) and air-cooling (5%) (Fig. 2b). Air-cooling is a relatively new technology and 90% of its capacity is located at new plants in China and India. About 22% of global coal-fired operating capacity is cooled with seawater, while the remaining 78% uses freshwater.

Our analysis of the CFPP capacity facing water scarcity by cooling technology shows that 60% (728 GW) of units with wet-cooling towers face water scarcity for at least one month per year. Because of their lower water intensity (Fig. 3), air-cooled systems are usually implemented in newly built units located in arid and/or water-scarce areas. In fact, we find that 72% (67 GW) of CFPPs cooled with air-cooled systems are facing water scarcity. These air-cooled CFPPs are located in regions that are so dry that even the little amount of water they use is depleting environmental flows and groundwater stocks. Because 56% (360 GW) of the once-through cooled capacity uses seawater as a cooling medium, these plants are not affected by water scarcity. Only 6% (36 GW) of once-through generating capacity is exposed to water scarcity. China has 62% (403 GW) and 74% (53 GW) of its wet-cooled and air-cooled CFPPs, respectively,

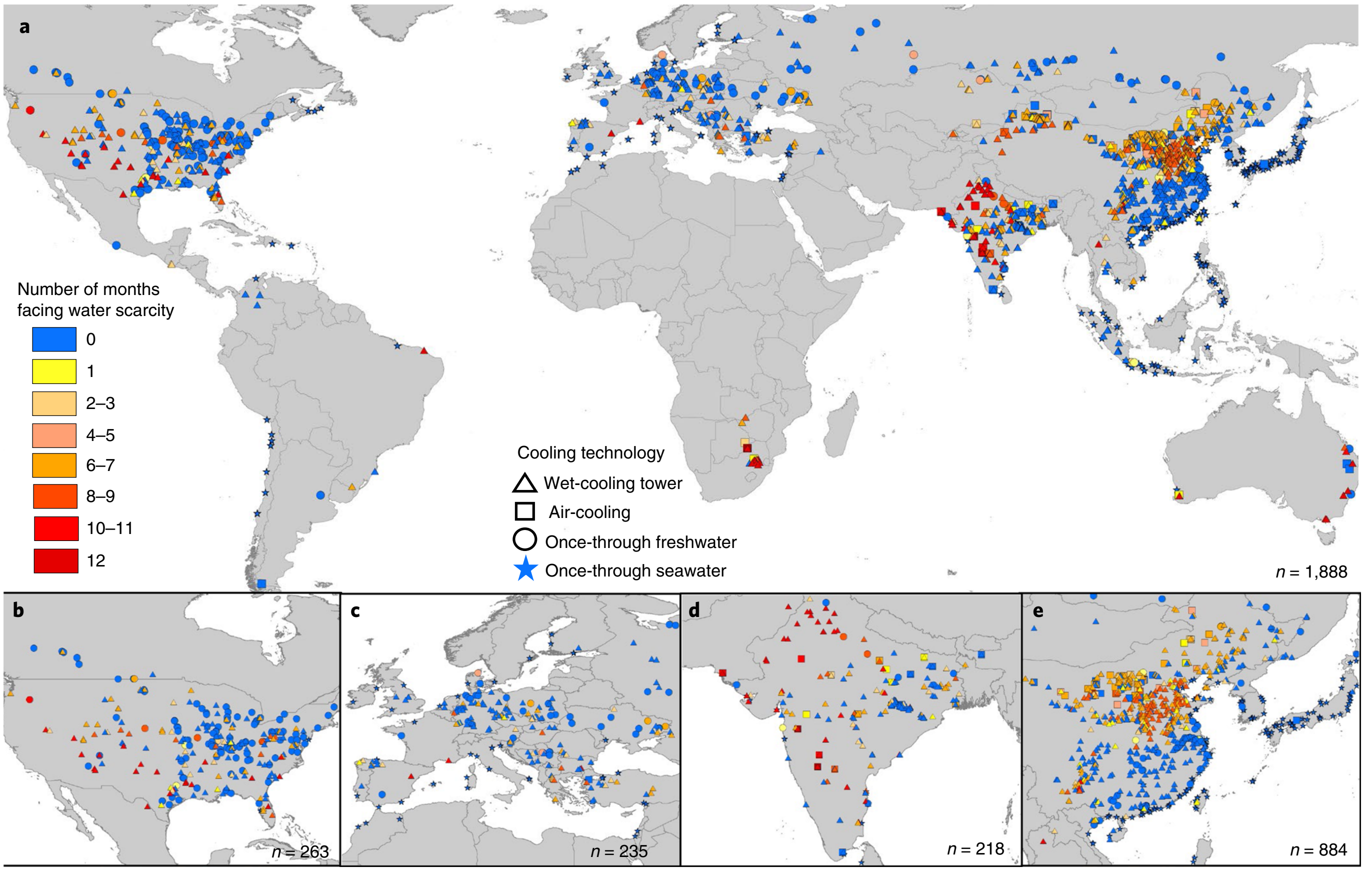

Fig. 1 | Geospatial distribution of coal-fired plants facing water scarcity in the 2011–2015 period. a, Location, number of months per year facing water scarcity and cooling technology of 1,888 coal-fired plants (*n*) worldwide. **b–e**, The four main regions where CFPPs are located: United States (**b**), Europe (**c**), India (**d**) and China (**e**). CFPPs facing water scarcity appear either in intensively irrigated areas (for example, high plains in the United States), in regions with high population densities (Pretoria, Johannesburg conurbations), or in irrigated and populated areas (North China Plain, India). Water scarcity also occurs in arid regions with a well-defined dry season (western United States, India, Australia, and Xinxiang and Inner Mongolia provinces in China). Generating units with once-through cooling are shown, distinguishing between the use of seawater and freshwater as the cooling medium.

exposed to at least one month of water scarcity per year (Fig. 2b). The United States and India have 60% (89 GW) and 63% (113 GW) of their wet-cooled CFPPs exposed to water scarcity for at least one month per year.

Future water scarcity with CCS

Using the water balance approach described above, we turn to an important aspect of future decisions regarding CCS, namely to what extent the available freshwater resources would allow for the adoption of CCS as a means to curb carbon emissions from existing CFPPs. Meeting humanity's burgeoning energy and water demands while avoiding an increase in anthropogenic CO_2 emissions and protecting environmental water flows is one of the most pressing challenges of this century.

Given that old, small (<100 MW) and low-efficiency CFFPs without environmental control systems will probably be shut down before being retrofitted with expensive CCS technologies, we assumed that only 1,093 large (>100 MW) CFPPs that began operating after 2000 will be retrofitted with CCS. We assume that these CFPPs will capture 90% (ref. [26]) of their CO_2 emissions by 2020. Because of this relatively short timeframe, we assume that water availability and coal-fired generation would not substantially change compared with current values. This scenario allows us to establish an upper bound on the potential impacts of CCS retrofit on water resources. Moreover, this assumption is likely a conservative scenario compared with the urgent need to drastically reduce global CO_2 emissions from CFPPs to meet climate targets[39]. This analysis provides the estimated additional water withdrawals and consumption from coal-fired generators based on (1) 1,888 existing CFPPs and (2) four hypothetical scenarios where the 1,093 large CFPPs that began operating after 2000 are retrofitted with CCS units.

Water requirements of CCS

Our estimates show that the difference in the overall water intensity of CFPPs with and without CCS technologies depends strongly on the type of cooling system and CCS technology (Fig. 3). Water intensity from air-cooling and once-through cooling technologies can differ by up to 4% with different air temperatures, relative humidities and gross power inputs, while with wet-cooling technology, water intensity can vary by up to 20%. CFPPs with wet-cooling towers retrofitted with CCS units have the highest water consumption intensity, while CFPPs with once-through cooling technology have the highest water withdrawal intensity. Independent of the cooling system, the least water-intensive CCS technologies are solid sorbent PSA and membrane systems.

An analysis of water usage by CFPPs shows a substantial increase in water consumption when four different CCS technologies are retrofitted. The current total global water consumption by CFPPs is $9.66\,km^3\,yr^{-1}$; 88% of this is sourced from freshwater, while the remaining 12% is sourced from seawater (Fig. 4). China, with 48% of the world's CFPP capacity, also consumes the greatest share of freshwater (53%), followed by India (16%) and the United States

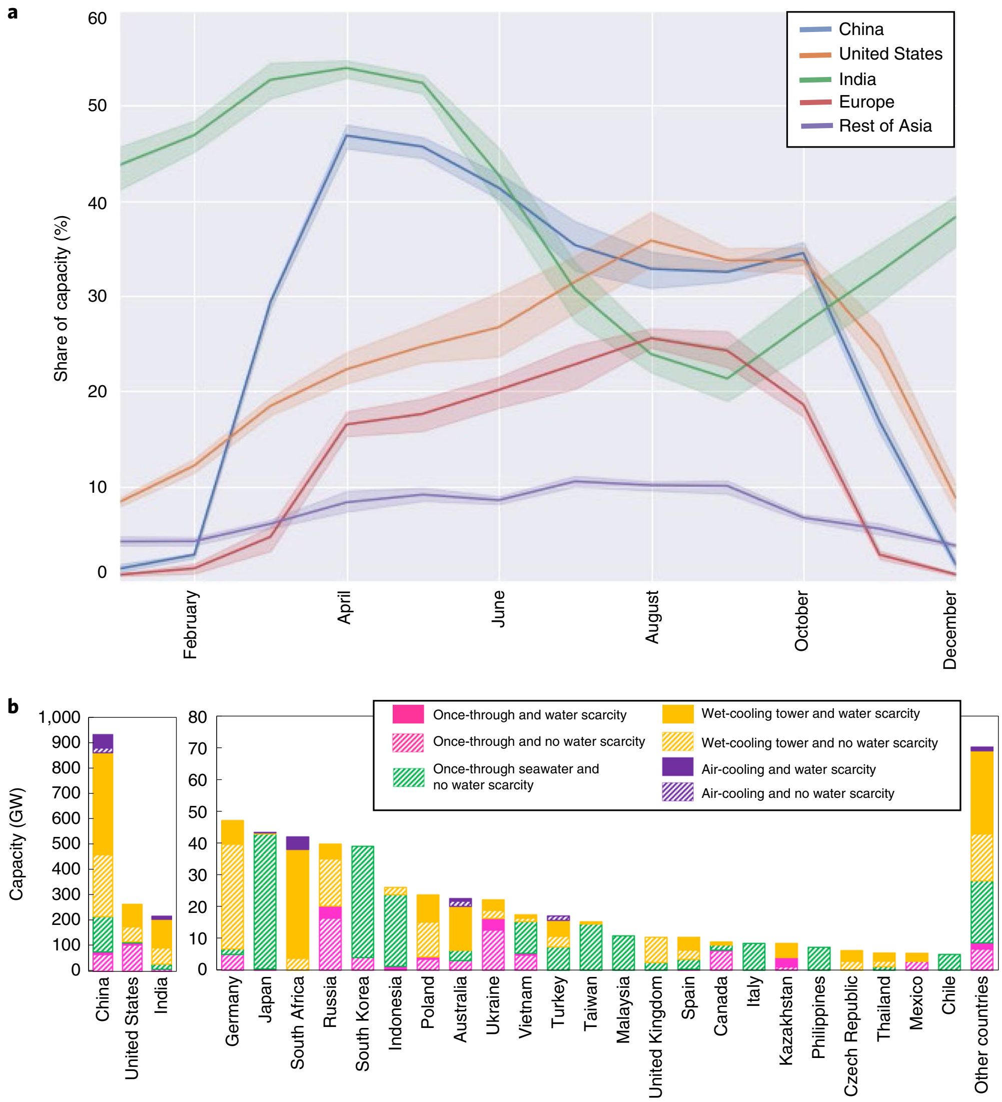

Fig. 2 | Exposure of CFPPs to water scarcity. a, The regional share of coal-fired operating capacity facing water scarcity each month of the year. Solid lines represent average water scarcity in the 2011–2015 period; shaded areas show interannual variability of water scarcity in the years from 2011 to 2015. **b**, The coal-fired capacity facing average water scarcity (for at least one month per year) by cooling technology; the currently installed coal-fired capacity and respective cooling systems are shown by country (or region).

(13%). By retrofitting CFPPs that began operating after 2000 with off-the-shelf amine absorption technology[27,40], global water consumption by CFPPs would increase by 50% (4.81 $km^3 yr^{-1}$). If these CFPPs were all retrofitted with membranes, water consumption would increase by 31% (3.00 $km^3 yr^{-1}$). Water consumption would increase by 32% (3.13 $km^3 yr^{-1}$) and 42% (4.07 $km^3 yr^{-1}$) if these CFPPs were retrofitted with solid sorbent PSA and solid sorbent TSA, respectively. Assuming that current CFPPs cooled with seawater will use seawater when retrofitted with CCS, 0.69–1.10 $km^3 yr^{-1}$ of this additional water consumption would come from seawater, while the remaining fraction (2.31–3.71 $km^3 yr^{-1}$) would be taken from freshwater bodies. Similar results can be found in terms of water withdrawals (Fig. 4).

Exposure to water scarcity with CCS

Retrofitting CFPPs with CCS units would create or exacerbate water scarcity conditions compared with current operations. Amine absorption and solid sorbent TSA technologies would most severely impact water resources. By retrofitting CFPPs that began operating after 2000 with these two technologies, an additional 13 GW (1%) of CFPP capacity would face water scarcity. Moreover, an additional 23% (232 GW) of CFPP capacity would be exposed to water scarcity for at least one additional month a year (Fig. 5). Because of their lower water intensities, membranes and solid sorbent PSA would increase water scarcity for only 18% and 20% of CFPP capacity, respectively (Supplementary Fig. 10). If CFPPs in China and India were retrofitted with commercially available amine absorption technology, an additional 168 GW and 52 GW of coal-fired capacity would be exposed to longer periods of water scarcity every year (Fig. 5b). In other words, in China and India 23% and 37% of CFPPs that began operating after 2000, respectively, would be vulnerable to longer periods of water scarcity with CCS installed.

Trade-offs between climate mitigation and water resources

This study highlights the water demands of coal-fired power generation and the potential water scarcity that would result from the adoption of CCS to address the associated CO_2 emissions. Our results show that cooling systems and CCS technologies have

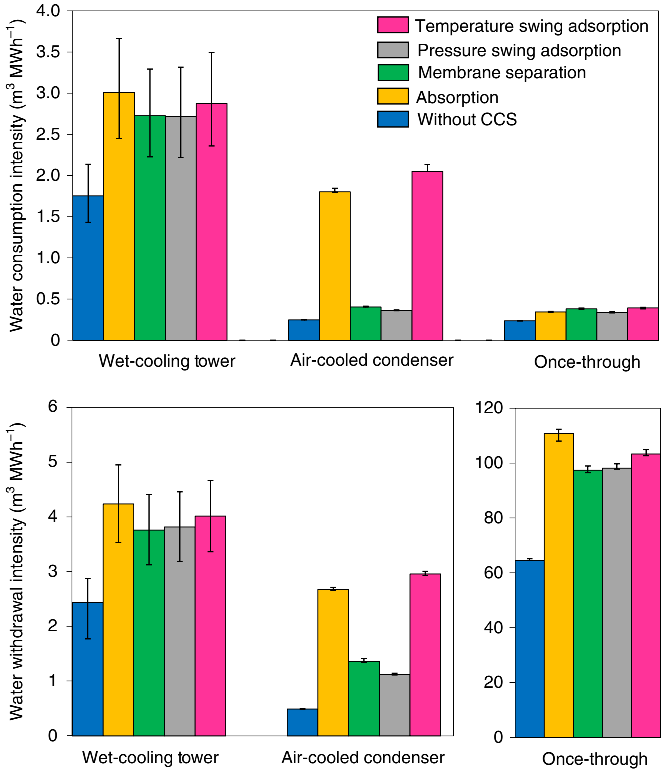

Fig. 3 | Water consumption and withdrawal intensities of CFPPs with and without CCS. The data were generated by running the IECM (version 11.2)[38] and considering the different monthly air temperatures, relative humidities and gross power inputs of the 1,888 CFPPs considered in this study. Interval bars represent maximum and minimum values of water intensities. Note that water withdrawal intensity with once-through cooling technology is shown on a different scale. Water intensities are expressed in terms of net power generation.

different water requirements, in terms of both consumption and withdrawal. For CFPPs located in water-scarce areas, the additional water consumption required by CCS (Fig. 4) could create competition with other human activities for local water resources[41,42] and/or generate unsustainable water consumption at the expense of aquatic ecosystems and freshwater stocks[43,44]. Therefore, the choice of CFPP cooling and CCS technologies is fundamental to avoid such competition. Worldwide the additional water requirements of CCS are dwarfed by freshwater demand from irrigation in the agriculture sector (Supplementary Table 1). Modest improvements in the efficiency of irrigation would free up enough freshwater for aquatic habitats and other human uses such as CCS.

The finding that 32% of CFPPs are exposed to water scarcity for at least five months per year suggests that these coal-fired units might not be well suited for retrofitting with CCS unless alternative water sources are available. The locations where CFPPs are likely to be retrofitted with CCS are mainly in India and China (Fig. 5), where 80% (858 GW) of global CFPP capacity has been built since 2000 and where plants generating an additional 309 GW are planned or under construction[25]. We find, however, that in these two countries a vast proportion of CFPP capacity is already exposed to water scarcity, and the addition of CCS would further exacerbate the vulnerability to water scarcity and potentially even impede CCS operations. Decision-makers, energy corporations and investors will have to consider the trade-offs between the climate change mitigation benefits of CCS and the increased demands it places on scarce local water resources.

Discussion and conclusions

Constraints on water availability already influence the location of power plants planned for the near future and the choice of cooling technologies for these installations. In China, the need to adapt to growing water scarcity has resulted in fewer water-intensive cooling systems in new power plants and when refurbishing existing CFPPs[16,45]. Investors are also becoming increasingly concerned about the effects of water scarcity. For instance, because wind and solar power production require less water than once-through coal-fired plants, UBS, a global leading investment firm, is recommending its investors buy low-water-intensive wind-power assets and sell coal-fired assets to avoid exposure to risks associated with water scarcity[46]. Moreover, energy corporations and investors should pay more attention to water as a risk for their business operations when they consider investing in CFPPs. As such, our findings have important implications for future investments in the global coal power sector.

We tested the sensitivity of our results to different environmental flow requirements, which are by far the largest factor affecting our findings. With the current assumption that 80% of the available water needs to be allocated to environmental flows, we find that 43% and 32% of global CFPP capacity faces water scarcity for at least one and five months per year, respectively. By adopting the less conservative variable monthly flow method[47], the fraction of CFPP capacity facing at least one and five months of water scarcity decreases to 39% and 23%, respectively.

In attempting a global analysis such as the one presented in this study, some approximations need to be made and data limitations are inevitable. Water consumption by CFPPs can vary by as much as 20%, depending on coal type, combustion technology, plant efficiency, plant size and environmental control systems[33]. Because Global Coal Plant Tracker—the dataset containing the CFPP inventory used in this study—does not provide information on these factors, we tested the sensitivity of our water scarcity analysis by increasing and decreasing monthly water consumption estimates of each CFPP by 20%. We find that our results show little sensitivity to this change in water consumption by CFPP. When we increase water consumption, we find that 44% and 34% of global CFPP capacity would face water scarcity for one to five months per year, respectively. By reducing monthly water consumption of each CFPP by 20%, we find that 42% or 30% of global CFPP capacity would by exposed to water scarcity for one to five months per year, respectively.

The twin costs of mitigating climate change and competing for water resources are vexing factors in managing energy systems. In an increasingly water-scarce and carbon-enriched world, governments will take specific actions targeting CO_2 emissions and water-intensive technologies, and investors may want to know whether new environmental policies could reduce the viability of coal-fired power generation with CCS systems. Our results enable a more comprehensive understanding of water uses by CFPPs and can better inform the management and policy decisions that are critical for a sustainable allocation of water resources in energy production. For CFPPs located in water-scarce areas, trade-offs between the climate change mitigation benefits and the increased pressure on water resources created by CCS should be weighed. This study shows that the water requirements of CCS technologies should be taken into account when evaluating future CCS scenarios because it is crucial to mitigate emissions from the energy sector without compromising on the sustainable use of water resources. Because refineries, natural gas power plants, and steel and concrete factories can also be retrofitted with CCS, the analysis presented in this study can be extended beyond the case of CFPPs.

Methods

This analysis begins with the identification through aerial imagery of cooling types and type of water source used as a cooling medium by 1,888 global CFPPs.

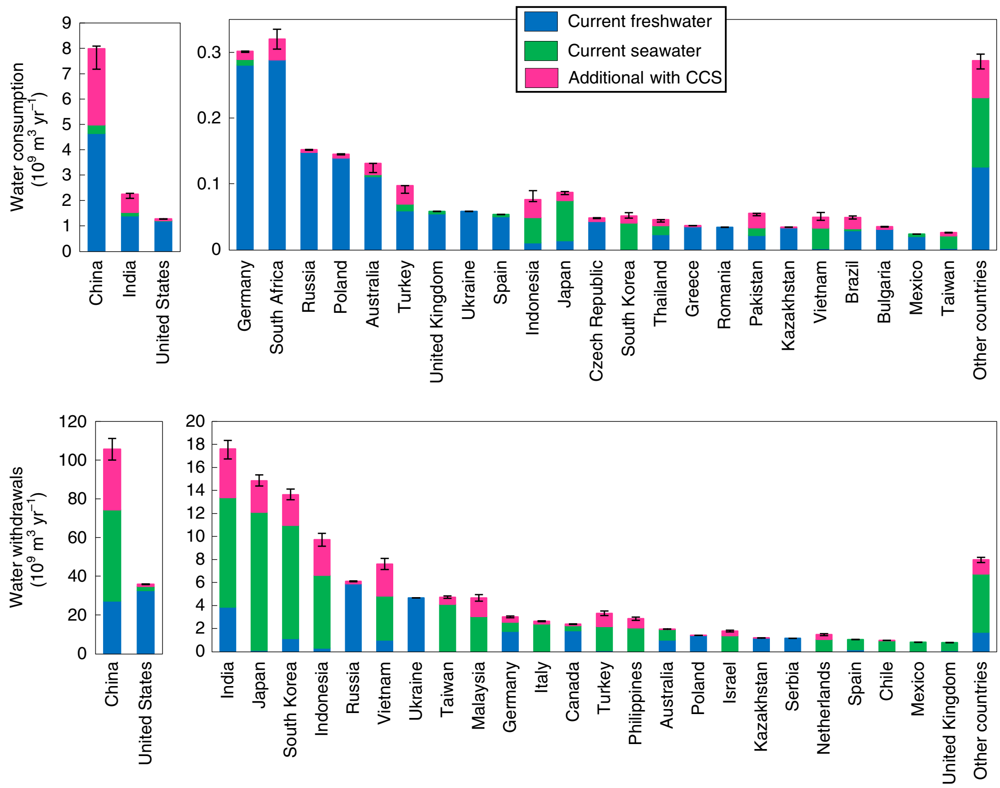

Fig. 4 | Water consumption and withdrawals of CFPPs with and without CCS. Current water consumption and withdrawals from 1,888 CFPPs, differentiated between freshwater and seawater. Additional water consumption and withdrawals from the 1,093 CFPPs that began operating after 2000 include both freshwater and seawater. Note that countries (or regions) are listed in descending order of current water consumption and withdrawals by CFPPs. Interval bars represent the maximum and minimum values of water consumption and withdrawals (seawater and freshwater combined) considering the four CCS scenarios assumed in this study. Current water withdrawals from CFPPs total 204 km^3 yr^{-1}. Of this volume, 43% is sourced from freshwater, while the remaining 57% is sourced from seawater.

We then run the IECM using the 'Baseline Power Plant' configuration, and on the basis of power-plant-specific monthly air temperature, cooling type and gross power inputs, we assessed water consumption and water withdrawal intensities for each CFPP under each scenario. Third, for each CFPP and scenario we assessed its monthly water consumption and withdrawal. Finally, for each scenario, we assessed water scarcity by accounting for water consumption by CFPPs. A detailed description of the methods used in this study is presented in the following sections.

Global coal-fired plant database. Global Coal Plant Tracker (update as of July 2018)[48] provides an inventory of all CFPPs with a capacity >30 MW existing around the world. It reports information about location, status, capacity, operating company, plant name and year of construction of coal-fired units with a total global estimated operating capacity of 2,003 GW (as of July 2018). The status is classified as 'announced', 'pre-permit', 'permitted', 'in construction', 'shelved', 'cancelled', 'operating', 'mothballed' or 'retired'.

Here we focus only on 'operating' coal-fired units with a capacity >100 MW, assuming that investments in CCS retrofitting would not be justified in the case of smaller units. Multiple units belonging to the same CFPP were aggregated into a single power plant. The operating large CFPPs that meet the above criteria account for 1,927 GW or 96% of total estimated operating capacity from coal-fired plants worldwide[48]. For all these CFPPs, we used aerial imageries from Google Earth to identify cooling types (wet-cooling tower, air-cooled condenser and once-through systems) and the water source used as a cooling medium (seawater or freshwater). Determining cooling technology and cooling water source of CFPP by visual inspection using aerial images has been proved an effective way to fill gaps existing in available data on power plant cooling systems[16,49]. Wet-cooling tower systems are equipped with cooling towers, air-cooled condensers are equipped with air-cooling islands, and once-through cooling systems do not have such cooling systems and are located close to large water bodies. Visual inspection results were also cross-checked when possible with information provided by the operating company listed in the Global Coal Plant Tracker[48].

Assessing water intensities of CFPPs with and without CCS. We assessed water consumption intensity and water withdrawal intensity (m^3 MWh^{-1}) from CFPPs using the Baseline Power Plant configuration of the IECM (version 11.2) developed by Carnegie Mellon University for the US Department of Energy's National Energy Technology Laboratory[38]. The IECM is a well-documented, publicly available model that provides systematic estimates of performance and emissions for fossil-fuelled power plants with or without CCS systems[29,38]. Water intensities in the IECM account for the parasitic energy demand of the CCS process. Therefore, the Baseline Power Plant configuration in the model assumes that the additional power required to perform CCS is taken at the expense of the plant efficiency and therefore less heat and power would be generated. Moreover, the Baseline Power Plant configuration in the IECM considers that each CFPP is retrofitted with environmental control systems (selective catalytic reduction, electrostatic precipitator and wet-flue gas desulfurization). We considered the water use by these environmental control systems both in the scenarios with and without CCS.

For each coal-fired unit, water intensity was assessed by considering (1) a current scenario and (2) four hypothetical future scenarios. In the current scenario, we assessed the water intensity of each CFPP by considering its cooling system (wet-cooling tower, air-cooled condenser and once-through). In the future scenario, we assumed that only CFPPs that began operating after 2000 (1,093 CFPPs or 1,018 GW) will be retrofitted with CCS units utilizing one of four different CCS technologies: absorption with amine solvents, membrane separation, and PSA and TSA capture systems. For each scenario and for each unit, we assessed water intensity considering local average monthly air temperature and gross power input. Average monthly temperatures at 5 × 5 arcminute resolution were taken from Fick et al.[50] Coal type (anthracite, lignite, bituminous, sub-bituminous), combustion technology (supercritical, subcritical, ultrasupercritical), plant efficiency, plant size, environmental control systems (selective catalytic reduction, electrostatic precipitator and wet-flue gas desulfurization for removing nitrogen oxides, fly ash and SO_2, respectively, from the flue gas), and CO_2 capture level are other factors that influence the water intensity of a CFPP[33]. Because the Global Coal Plant Tracker database used in this study does not contain detailed information about these factors, we tested the sensitivity of our results to ±20% changes in monthly water consumption in each CFPP.

For each CFPP, we assessed monthly water consumption and water withdrawals (m^3 month^{-1}) by multiplying its monthly water intensity (m^3 MWh^{-1}) times the coal-fired unit capacity by a 50% capacity factor and the number of hours in each

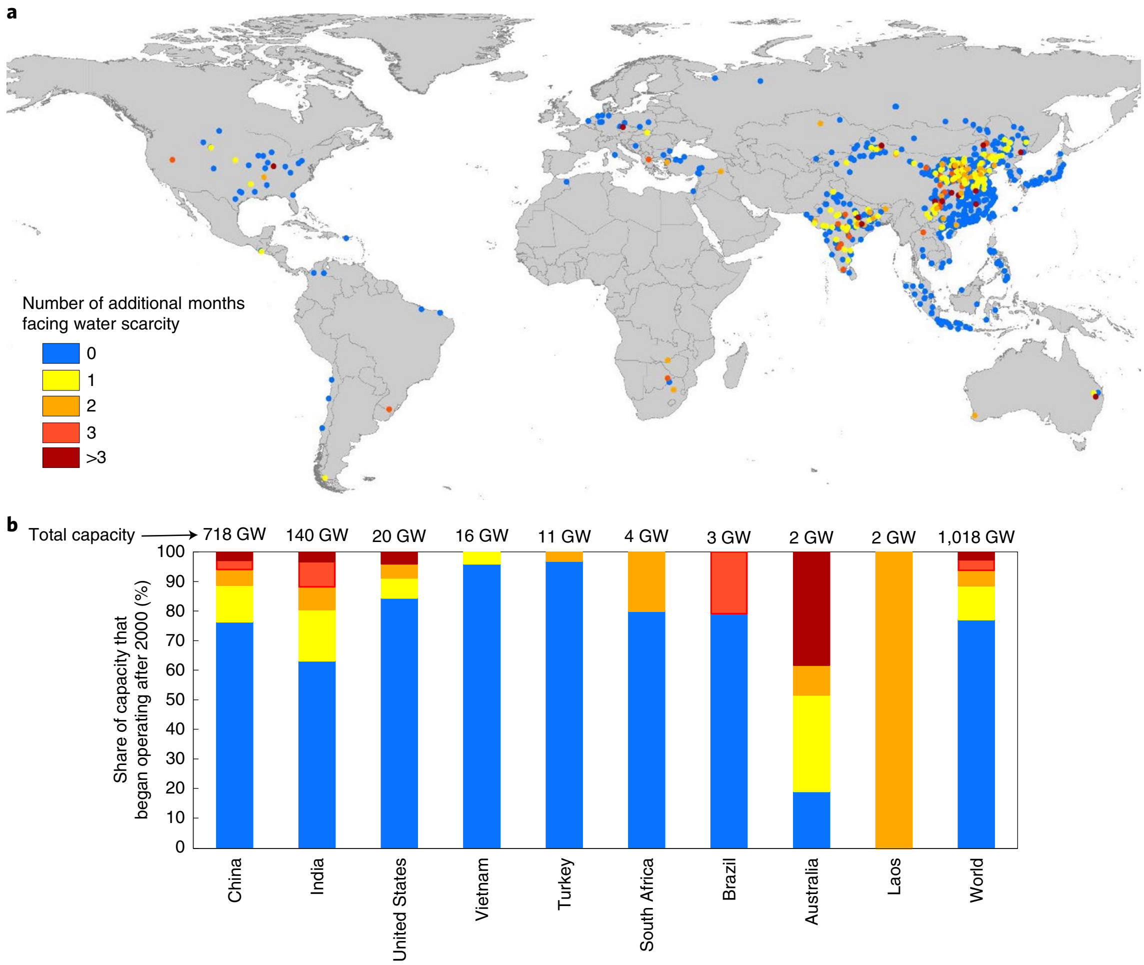

Fig. 5 | Additional water scarcity with amine absorption carbon capture technology. The number of additional months of water scarcity per year that CFPPs that began operating after 2000 would face if they were retrofitted with commercially available amine absorption technology. **a**, The geographical distribution of CFPPs that began operating after 2000 and the number of months of additional water scarcity these plants would face if retrofitted with amine absorption. **b**, Country-specific share of coal-fired capacity that began operating after 2000 that would face additional months of water scarcity if retrofitted with amine absorption technology. Countries are listed in descending order based on additional capacity facing water scarcity.

month. The 50% capacity factor is a conservative assumption given that the global average capacity factor of coal-fired plants was 52.5% in 2016 (ref. [13]), and also considering that we are experiencing a reduction in coal use because of natural gas conversion[51,52].

Water scarcity analysis. Monthly water scarcity (WS, 5 × 5 arcminute resolution) was assessed by combining the monthly availability and consumption of freshwater resources. CFPPs are located in water-scarce areas if the ratio between freshwater consumption (WC) and available water (WA) is >1 (ref. [22]):

$$WS = \frac{WC}{WA} > 1$$

This methodology to evaluate water scarcity has been extensively validated in studies aiming at analysing the influence of energy and agricultural production on water resources[22,42–44,53]. Water consumption accounts for freshwater consumption for irrigation, domestic use and CFPPs. For this reason, CFPPs cooled with seawater were not considered in the water scarcity analysis because they do not consume freshwater in their operations. Monthly available water (5 × 5 arcminute resolution, or ~10 km at the Equator) was calculated as the difference between monthly blue water flows generated in that grid cell and the environmental flow requirement. Monthly blue water flows (2011–2015 period) were assessed by adding up, for every cell, routed river discharge and groundwater discharge. Discharge data were taken from PCR-GLOBWB-2 outputs[54,55]. Upstream water consumption and its unavailability for downstream uses were accounted for by considering—for every cell of the landscape—all water uses (agriculture, industrial, municipal and environmental flows). Irrigation water consumption (5 × 5 arcminute resolution) was taken from Rosa et al.[44] and was assessed using a process-based crop water model that estimates irrigation water consumption for major crops. Domestic water consumption (5 × 5 arcminute resolution) was taken from Hoekstra and Mekonnen[56] and assessed using country-specific per-capita values multiplied by the local population taken from population density maps. We assumed that CFPPs cooled with seawater face no water scarcity and only land-based water plants are at risk of water scarcity. Because the irrigation water consumption dataset used[44] was generated for a five-year time period, we here used the same five years of discharge data[54,55] to assess interannual variability of water scarcity. Although this time period might be too short to capture a full range of extreme wet and dry periods, our results are robust and show little sensitivity to different environmental flow requirements, which are by far the largest factor affecting our results.

Environmental flow is here defined as the minimum freshwater flow required to sustain ecosystem functions. Environmental flow requirements were accounted for in our water scarcity analysis, assuming that 80% of the monthly blue water flows should be preserved for environmental flow protection (that is, remain unavailable to human consumption) to maintain ecosystem functions[57]. We tested the sensitivity of our results to the less conservative variable monthly flow method[47], which accounts for intra-annual variability in discharge by classifying flow regimes into high-, intermediate- and low-flow months.

Caveats. Although a 100% adoption of CCS technology is not a realistic scenario, this assumption allows us to assess the impacts of CCS retrofit on water resources. Moreover, this assumption is in line with the urgent need to drastically reduce global CO_2 emissions from CFPPs to meet climate targets[39]. The goal of our study is to determine the water requirements and the exposure to water scarcity of CFPPs with and without CCS. We are not trying to determine future likely CCS adoption scenarios. The research question we want to answer is: are there enough water resources for a massive adoption of CCS to curb emissions from coal-fired power plants? Thus, our analysis is conservative because we now consider that all the coal plants that began operating after 2000 will be retrofitted with CCS. Of course, the adoption of less 'aggressive' socioeconomic pathways can lead to different scenarios of CCS application in the electricity sector. A partial adoption of CCS technology would entail a lower pressure on the water system. We also stress that in this study we consider four different scenarios of CCS technologies (amine, membrane, and solid sorbent PSA and TSA). These CCS scenarios are meant to be illustrative, rather than representative of future capacity expansion and CCS deployment.

Our results are based on a biophysical model and on assumptions that are always necessary in any global modelling study. First, decisions to retrofit existing plants with CCS are complicated and involve many factors such as plant age and size, economic viability, land restraints and location close to geological formations suitable for carbon storage. The analysis of these factors falls outside the scope of this work. We also do not consider the potential impacts that CO_2 storage could have on regional groundwater quality and therefore water availability[58,59]. Second, we assumed that current power plants cooled with seawater will also withdraw and consume seawater (in the same proportion) when retrofitted with CCS. Third, while our water balance model considers water consumption and accounts for the need to protect environmental flows that are crucial to the health of freshwater ecosystems, it does not evaluate other environmental and economic impacts associated with water withdrawals from coal-fired plants, which involve local effects that a global analysis fails to assess. Moreover, quantifying water scarcity using water withdrawals might overestimate water scarcity since return flows can be used multiple times. For example, water withdrawals in the Colorado River Basin exceed water availability because of substantial reuse of return flows. Therefore, we assessed water scarcity using water consumption. Fourth, because hybrid cooling technology (wet-cooling paired with air-cooling) is a relatively new technology, we did not consider this cooling technology in our analysis. Fifth, power plants located in water-scarce areas are unlikely to remain water stranded in the sense that they are expected to continue their operation in months of water scarcity by sourcing water through interbasin water transfers, artificial reservoirs, mining non-renewable groundwater, building desalination plants or using water at the expense of environmental flows. Alternatively, water stranding can be avoided by lowering power production or by retrofitting CFPPs with emerging technologies that have lower water intensity (for example, air-cooled systems)[16], albeit at the expense of increased energy consumption and economic costs[60,61]. Furthermore, there are also opportunities to use desalinated brine from saline CO_2 sequestration aquifers to provide alternative freshwater sources and offset the additional water requirements of CCS[34]. These are economic, institutional and non-biophysical factors that our hydrological model was unable to take into account. Moreover, energy corporations can prevent a shut-down (and associated losses) during periods of water scarcity by buying water from other sectors (typically agriculture, in the presence of tradeable water rights) and paying more attention to water as a risk for their business operations[46]. Today, the reliability of coal-fired generators is quite high in the sense that they rarely experience power losses associated with water availability limitations[15,62]. Curtailments or shutdowns during dry periods are seldom due to constraints in water availability but to the ability to cool down water when its temperature exceeds environmental regulatory thresholds for discharge in water bodies[62,63]. Increased water temperatures have led to curtailments in power generation worldwide[12,17]. Future improvements in the assessment of the vulnerability of CCS can possibly be achieved by accounting for water temperatures as a constraint to CCS adoption.

Lastly, our analysis considers the possibility of retrofitting global CFPPs with postcombustion CCS technologies. However, postcombustion CCS is an emerging technology not only for coal-fired generation but also for other industrial[64] and energy CO_2 sources[65,66]. Other technologies also could be deployed to capture carbon such as precombustion and oxy-combustion[27,67]. Another promising technology is to remove CO_2 from the atmosphere and generate negative emissions via bioenergy with CCS[68] or direct air capture[69].

Data availability

The data used to perform this work can be found in the Supplementary Information and in the reference list. Any further data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions
L.R. conceived the study, led the study design, data analysis, data collection and writing; J.A.R., M.S.W. and P.D. assisted with study design and writing.

Competing interests
The authors declare no competing interests.

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