Renewable and Sustainable Energy Reviews 138 (2021) 110511

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

The water footprint of carbon capture and storage technologies

Lorenzo Rosa [a,*], Daniel L. Sanchez [a], Giulia Realmonte [b], Dennis Baldocchi [a], Paolo D'Odorico [a]

[a] Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA, 94720, USA
[b] Business Innovation & Development, Edison S.p.A., Milan, IT 20121, Italy

ARTICLE INFO

Keywords:
Water footprint
Carbon dioxide removal
Carbon capture and storage
Negative emission technologies
Water scarcity
Sustainability
Climate change

ABSTRACT

Carbon capture and sequestration (CCS) is an important technology to reduce fossil CO_2 emissions and remove CO_2 from the atmosphere. Scenarios for CCS deployment consistent with global climate goals involve gigatonne-scale deployment of CCS within the next several decades. CCS technologies typically involve large water consumption during their energy-intensive capture process. Despite potential concerns, the water footprint of large-scale CCS adoption consistent with stringent climate change mitigation has not yet been explored. This study presents the water footprints (m^3 water per tonne CO_2 captured) of four prominent CCS technologies: Post-combustion CCS, Pre-combustion CCS, Direct Air CCS, and Bioenergy with CCS. Depending on technology, the water footprint of CCS ranges from 0.74 to 575 m^3 H_2O/tonne CO_2. Bioenergy with CCS is the technology that has the highest water footprint per tonne CO_2 captured, largely due to the high water requirements associated with transpiration. The widespread deployment of CCS to meet the 1.5 °C climate target would almost double anthropogenic water footprint. Consequently, this would likely exacerbate and create green and blue water scarcity conditions in many regions worldwide. Climate mitigation scenarios with a diversified portfolio of CCS technologies have lower impacts on water resources than scenarios relying mainly on one of them. The water footprint assessment of CCS is a crucial factor in evaluating these technologies. Water-scarce regions should prioritize water-efficient CCS technologies in their mitigation goals. In conclusion, the most water-efficient way to stabilize the Earth's climate is to rapidly decarbonize our energy systems and improve energy efficiency.

1. Introduction

Carbon capture and storage (CCS) is an important technology to reduce CO_2 emissions from electricity and industrial sectors, as well as to remove CO_2 from the atmosphere. Depending on the origin of CO_2, there are different technologies to realize CCS. Emissions pathway scenarios for carbon capture technologies deployment consistent with global climate goals show that it will be required to remove an additional 640–950 billion tonne of CO_2 from the atmosphere by the end of the century in order to stabilize global temperatures at or below 1.5 °C above preindustrial temperatures [1,2]. By removing CO_2 from the atmosphere and decarbonizing energy and industrial systems, CCS is one of the technologies that can play a key role in meeting climate change targets [3]. Since natural climate solutions are not large or fast enough to mitigate climate [4,5], CCS is receiving an increasing interest not only from the scientific community, but also from the international political community and the corporate world. For example, some major corporations are pledging to be carbon neutral and committing to sequester their historical CO_2 emissions in the next few decades [6]. As CCS seems ever more necessary [7], technology developers and policymakers should ensure these approaches reliably sequester CO_2 emissions and minimize unnecessary environmental impacts [8].

The twin challenges of managing climate change and water scarcity cannot be considered independently. For example, recent low carbon energy policies have had the unintended consequence of exacerbating tensions between food and energy systems with increased water requirements for biofuels production [9], hydropower generation [10,11], and afforestation for carbon sequestration [12–15]. Water is also becoming an increasingly important issue for low-carbon electricity generation [16–20]. Therefore, water is starting to be considered a major factor that will constrain humanity's ability to meet future societal needs while also managing climate change mitigation [21,22]. The expected adoption of CCS technologies [23,24] generates the need for more detailed information about their water footprints and how they

---

Abbreviations: CCS, Carbon Capture and Storage; BECCS, Bioenergy with Carbon Capture and Storage; DACCS, Direct Air Carbon Capture and Storage; CO_2, Carbon Dioxide.

* Corresponding author. Institute of Energy and Process Engineering, ETH Zurich, 8092 Zurich, Switzerland.

E-mail addresses: lorenzo_rosa@berkeley.edu, lorenzorosa92@gmail.com (L. Rosa).

https://doi.org/10.1016/j.rser.2020.110511
Received 27 April 2020; Received in revised form 4 August 2020; Accepted 22 October 2020

will interplay in the water-energy-food-climate nexus [25].

CCS systems are energy- and water-intensive technologies that, if adopted, will commit humanity to additional water use, further compelling attention to water scarcity [26]. CCS technologies use water during the cooling process at the power-plant level [27] and require additional water as an integral part to the carbon capture processes [28]. For example, it has been estimated that retrofitting a coal-fired power plant with post-combustion CCS would increase the power-plant water intensity by 55%, while decreasing the net plant efficiency by 45% [29]. Notably, bioenergy with CCS requires water during the carbon capture process at the power-plant level, but also additional water during biomass cultivation via evapotranspiration. Previous studies have assessed the water footprint of direct air CCS [30], bioenergy with CCS [8,31], and post-combustion CCS [26,28,29,32]. We, here, provide more comprehensive and detailed estimates of water footprints (Box 1) from a broad portfolio of carbon capture technologies, considering direct air CCS and bioenergy with CCS in addition to pre-combustion- and post-combustion- CCS technologies.

A successful solution towards mitigating climate change will curtail CO_2 emissions and minimize use of freshwater resources, especially in water-scarce regions. Despite the mounting concerns about global water scarcity, the water requirements of CCS technologies are often overlooked. As we continue to evaluate the cost-effectiveness of different climate change mitigation technologies, the assessment of the water footprints of different CCS technologies can provide relevant insights to inform policy makers about the implication of alternative scenarios.

This study gives a comprehensive overview of the water footprint (m^3 of fresh water per tonne CO_2 captured) of the four most prominent CCS technologies: (1) post-combustion CCS; (2) pre-combustion CCS; (3) Direct Air Capture Capture and Storage (DACCS); (4) Bioenergy with Carbon Capture and Sequestration (BECCS) (Box 2). Using future CCS adoption scenarios consistent with 1.5 and 2 °C climate targets [33], we estimate projected global water consumption associate with carbon dioxide removal by CCS throughout the 21st century.

2. Methods

The production of food, fiber, feed, and energy depends on the uptake and consumption of soil moisture (or green water) supplied by rainfall and freshwater from surface water bodies and aquifers (or blue water) (Box 1). Here, we assess the total water consumption from CCS. While pre-combustion CCS, post-combustion CCS, and DACCS use solely blue water in their processes, BECCS uses green water to produce biomass feedstock and then blue water in the capture and sequestration of carbon dioxide at the power plant. In the following section, we describe how we calculated the water footprint of four CCS processes.

2.1. *Calculation of the water footprint of post-combustion and pre-combustion CCS*

We assessed blue water footprints of post-combustion- and pre-combustion- CCS using the Baseline Power Plant configuration of the Integrated Environmental Control Model (IECM Version 11.2) developed by Carnegie Mellon University for the U.S. Department of Energy's National Energy Technology Laboratory (USDOE/NETL) [43]. The IECM Model is a well-documented publicly available engineering model that provides systematic estimates of water uses of coal fired- and natural gas fired-power plants with or without CCS systems. CCS processes are energy-intensive technologies [44] that would impose additional energy demands on existing power plants and thus require additional water for cooling processes. Water footprints vary depending on atmospheric temperature, relative humidity, cooling technology, and power plant capacity [26]. We run the IECM Model generating an ensemble of water footprints considering a range of atmospheric temperatures (from 0 °C to 30 °C), relative humidity (from 25% to 75%), power plant capacities (from 100 MW to 2500 MW), and cooling technologies (wet--cooling, air-cooling, once-through, and hybrid cooling). We also run the IECM model considering four post-combustion CCS processes (amine absorption, pressure swing adsorption, pressure swing adsorption, and membrane separation) and two pre-combustion CCS processes (oxy-combustion and integrated gasification combined cycle) (Box 2).

2.2. *Calculation of the water footprint of DACCS*

Water loss in DACCS processes come from the sorbent-air contacting process [24]. The blue water footprint of DACCS varies in function of temperature, relative humidity, and sorbent molarity [30]. The water footprint was assessed using the definitions and assumptions of Socolow et al., 2011 [45] (Page 40) and considering a range of temperatures (from 0 °C to 30 °C), relative humidity (from 25% to 75%), and two sorbent molarities (5 M and 10 M).

2.3. *Calculation of the water footprint of BECCS*

The water footprint of BECCS was assessed considering the water required to produce the biomass feedstock (or green water) and the water use in the carbon dioxide capture process (or blue water). To estimate the water required to produce biomass feedstock, we compiled an inventory of water use efficiencies (gH_2O per gCO_2) of different dedicated feedstock from existing studies (Table 1; Supplementary Table). Water use efficiency is a measure of the amount of water required by a biomass feedstock to sequester a certain amount of carbon dioxide [46, 47]. Water use efficiency is dependent on climate, phenology, latitude,

Box 1Concepts and definitions about water systems.

WATER CONSUMPTION is the volume of net water extracted. This water is evapotranspired and becomes unavailable for short-term reuse within the same watershed.

WATER WITHDRAWAL is the gross volume of water abstracted 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 uses.

WATER FOOTPRINT is the volume of fresh water consumed to produce goods or services during their life cycle [34,35]. Based on the source of the water, the water footprint can be divided in green and blue water footprint.

GREEN WATER Root-zone soil moisture that is available for uptake by plants. Biomass plantations use green water during the photosynthesis process.

BLUE WATER Freshwater in surface and groundwater bodies available for human use. All CCS technologies use blue water during the CO_2 capture process at the power-plant level.

GREEN WATER FOOTPRINT refers to water from the unsaturated root zone of the soil profile that is used by plants and soil microorganisms. It is relevant for the assessment of the water footprint of BECCS because of the evapotranspiration of water by biomass feedstock.

BLUE WATER FOOTPRINT refers to water from surface and groundwater bodies, it is relevant for the assessment of the water footprint of DACCS, and pre- and post-combustion CCS because of the evaporation of water at the power plant level during the capture and sequestration process.

Box 2Concepts and definitions about carbon capture and storage technologies.

CARBON CAPTURE AND STORAGE (CCS) is the process of trapping carbon dioxide (CO_2) produced by anthropogenic activities and storing it in such a way that it is unable to affect the atmosphere [41,42]. CCS is a critical technology for climate change mitigation, but most of these technologies are commercially immature [3]. CCS technologies typically involve large water consumption during their energy-intensive capture process.

CARBON SEQUESTRATION EFFICIENCY is the fraction of carbon in the biomass feedstock that is captured and sequestered through a CCS supply chain (Fig. 1)

TECHNOLOGY	TECHNOLOGY READINESS LEVEL [ref. 24] (from *1* to *9*; low to high maturity level)
DIRECT AIR CAPTURE AND STORAGE (DACCS) capture and permanent sequestration of CO_2 directly from the atmosphere [30,36]. Proposed processes entail using solid or liquid sorbents to capture CO_2. DACCS uses blue water during the energy-intensive capture process.	***8***. Small-scale of direct air capture technologies have found niche markets for greenhouses and synthetic fuels [37]. ***7***. Large-scale solid sorbent technologies have been built at demonstration-scale in Squamish, BC, Canada. Only one DACCS project exists, in Iceland [38].
BIOENERGY WITH CARBON CAPTURE AND STORAGE (BECCS) capture and permanent sequestration of biogenic CO_2 during energy conversion from biomass [39], including post-combustion and pre-combustion technologies. BECCS uses blue water during the energy-intensive capture process, and green water during biomass feedstock cultivation.	***9***. CCS from corn ethanol production has been practiced at commercial scale, both for enhanced oil recovery, and permanent geologic storage [39]. ***6-7***. Several plants are under development to produce transportation fuels from lignocellulosic biomass in or near California, United States [40].
POST-COMBUSTION CARBON CAPTURE AND STORAGE capture and permanent sequestration of CO_2 after the combustion process has taken place [41,42]. This process uses blue water during the energy-intensive capture process.	***8***. Post-combustion capture and sequestration is practiced at commercial scale at Boundary Dam Power Station in Saskatchewan, Canada. It is not yet in widespread commercial use.
PRE-COMBUSTION CARBON CAPTURE AND STORAGE there are two different processes: *Integrated gasification combined cycle* is a process that converts coal and biomass into syngas, capturing and sequestering CO_2 before the combustion process has taken place. *Oxycombustion* is the process of burning coal and biomass in pure oxygen, capturing and sequestering a pure stream of CO_2 after the combustion process has taken place [41,42]. These processes use blue water during the energy-intensive capture process.	***7***. Electricity generation via integrated gasification combined cycle with CCS was attempted, but ultimately abandoned, at the Kemper County energy facility in Mississippi, United States.

available water [48–51]. Blue water used to capture CO_2 in the combustion process of biomass was assessed using the IECM Model and considering the water footprint of integrated gasification combined cycle.

We consider two technology cases for BECCS: an efficient carbon supply chain, and an inefficient supply chain. Estimates of carbon sequestration efficiency were first estimated by Smith and Torn in 2013 [52] (Fig. 1a). Smith and Torn model an indirectly heated biomass integrated gasification combined cycle-CCS facility with relatively little heat integration [53], and assume very high losses of CO_2 during transport and injection [54]. In total, Smith and Torn estimate that 47% of carbon in the biomass feedstock is captured and sequestered in the integrated gasification combined cycle and CCS process [52].

We expect commercial applications of BECCS for power generation to achieve higher carbon sequestration efficiencies. In our efficient scenario, we model a carbon-efficient integrated gasification combined cycle facility with 90% CO_2 capture [57], and adjust losses during transport and injection to 1.8%. Baling losses were assumed to be 4% [56]. This figure is the low-range estimate of Brandt et al., 2014 [55], a comprehensive review of methane (CH_4) leakage rates. Large-scale CO_2 transportation and injection may incur similar losses to existing CH_4 systems. In total, we estimate a carbon sequestration efficiency of 81%. Both scenarios are shown in Fig. 1.

While the water footprint of pre-combustion CCS, post-combustion CCS, and DACCS is solely from blue water, the water footprint of BECCS is from both green water and blue water. Feedstock biomass growth uses both green water and in many cases blue water supplied by irrigation [31]; blue water is also used in the capture and sequestration process during the integrated gasification combined cycle. Here we assume that feedstock biomass is solely rain-fed and therefore only green water is used in the production of biomass.

2.4. *Calculation of projected water consumption*

We assessed projected water consumption from CO_2 sequestration in the 21st century multiplying technology-specific CO_2 sequestration from CCS processes (tonne CO_2) times their water footprints (m^3 per tonne CO_2). Carbon dioxide removal scenarios were taken from Realmonte et al., 2019 [33] and assessed using two well-established integrated assessment models – WITCH [83] and TIAM-Grantham [84]. With integrated assessment models, it is possible to evaluate the role of different carbon removal technologies in 1.5 and 2 °C mitigation scenarios through a least-cost optimization, under a range of techno-economic assumptions (technology costs, energy requirements, and technical learning and growth rates). These scenarios were obtained imposing a carbon budget over the 2016–2100 period equal to 810 and 220 billion tonne CO_2, consistent with 1.5 °C and 2 °C warming respectively [85]. We chose the study of Realmonte et al., 2019 [33] for its detailed representation of a broad portfolio of carbon capture technologies, considering also DACCS and BECCS in addition to traditional CCS processes. Moreover, the inter-model study design ensures that our results are robust across model uncertainties, as the integrated assessment models adopted have complementary characteristics.

3. Results

3.1. *Water footprint of low carbon electricity generation*

Water use is becoming an increasingly important issue for low-carbon electricity generation [86]. Given the committed trillion-dollar investments in existing fossil fueled energy and industrial infrastructure [87], post-combustion CCS is the preferred economically viable technology to curtail CO_2 emissions because it can potentially be added to existing energy and industrial infrastructure without having to decommission them [88,89]. Using the IECM model, we estimate that a coal-fired power plant retrofitted with post-combustion CCS has a water footprint of 1.71 [0.50; 2.33] m^3/tonne CO_2 (*median* [*low percentile; upper percentile*] *across the ensemble*) (Fig. 2). Receiving increasing attention is also the opportunity to retrofit natural gas power plants with post-combustion CCS [90]. We estimate that a natural gas combined cycle power plant retrofitted with post-combustion CCS has a water footprint of 2.59 [2.37; 3.16] m^3/tonne CO_2.

Fig. 3 shows technology-specific water intensities of different post-combustion CCS technologies. We find that water intensity strongly varies with cooling technology and CCS technology (Fig. 3). Once-through is the cooling technology with the highest water withdrawal intensity, while wet cooling is the technology with highest water consumption intensity. Amine absorption and temperature swing adsorption are the CCS technologies with the highest water intensity. Pressure swing adsorption and membranes systems are the least water intensive CCS technologies.

Pre-combustion CCS is another promising technology to decarbonize energy and industrial systems (Box 2). We considered two pre-combustion CCS processes: Oxy-combustion and integrated gasification combined cycle. We find that oxy-combustion has a similar water footprint to post-combustion CCS, equal to 2.22 [1.93; 2.69] m^3/tonne CO_2. But integrated gasification combined cycle has a smaller one, equal to 0.74 [0.65; 0.80] m^3/tonne CO_2 (Fig. 2).

3.2. Water footprint of carbon dioxide removal

Preventing global temperature from rising more than 1.5 °C is likely to require the removal of CO_2 from the atmosphere with negative emission technologies such as BECCS and DACCS [91,92]. BECCS is the CCS technology with the highest water footprint. Under a low efficiency configuration (Fig. 1a), BECCS has a water footprint equal to 575 [382; 766] m^3/tonne CO_2 captured, while under a high efficiency configuration (Fig. 1b), it has a lower water footprint equal to 333 [221; 444] m^3/tonne CO_2 captured (Fig. 3). The water footprint of BECCS is mainly from green water to grow biomass feedstock. Fig. 4 shows the water footprint of BECCS considering different dedicated biomass feedstock. The water footprints show large variations depending on feedstock type and phenology. Producing bioenergy and capturing CO_2 from eucalyptus plantations has the highest water footprint (Fig. 4), while miscanthus and willow are the biomass feedstock with the lowest water footprint. In addition to BECCS, DACCS is emerging as a potentially important process to remove CO_2 from the atmosphere [34]. Despite DACCS is currently more expensive than BECCS, we find that DACCS is the most water-efficient way to remove CO_2 directly from the atmosphere, with a blue water footprint of 4.01 [2.00; 6.83] m^3/tonne CO_2.

3.3. Projected water use to meet climate targets

In order to assess the water consumption that would result from the adoption of CCS to meet 1.5 °C and 2 °C climate change targets in the 21st century, we multiplied the projected amount of CO_2 sequestered by different technologies [33] by the water footprint values specific to each CCS process. Under a more conservative 2 °C climate change scenario, CCS would have a water footprint of 3900–5850 km^3 to sequester 15–47 billion tonne CO_2 yr^{-1} in year 2100 (Fig. 5). We also find that meeting 1.5 °C mitigation targets will require substantially more water than the 2 °C climate scenario, with an estimated 5085–8564 km^3 of water necessary to sequester 21–47 billion tonne CO_2 yr^{-1} in year 2100. The 1.5 °C climate scenario will require more water because more CO_2 will need to be sequestered from the atmosphere along the century to limit warming. In all the scenarios, more than 97% of global water consumption will come from BECCS and therefore would mainly be from green water. Indeed, Fig. 5 shows that the scenarios with multiple adoption of CCS technologies exhibit lower water consumption, while BECCS intensive scenarios require more water than the others do.

Table 1
Inventory of previous studies used to collect data of water use efficiencies of biomass feedstock for BECCS. The actual water use efficiencies obtained from these studies are shown in Supplementary Table 1.

BIOMASS FEEDSTOCK	SOURCE
POPLAR	[58–62]
MISCANTHUS	[63–68]
CROP RESIDUES	[66,70,71]
EUCALYPTUS	[72–76]
SWITCHGRASS	[66,68,71,77–79]
WILLOW	[80–82]
PERENNIAL GRASSES	[67–69]

While our results show that large volumes of water will be required, future technological development could lower the water footprint of CCS processes. For example, to assess the water footprint of BECCS we considered a carbon conversion efficiency – the amount carbon from the harvested dedicated feedstock can be removed from the carbon cycle and sequestered – equal to 47% [52] (Fig. 1). In case the carbon conversion efficiency of BECCS increased to 81% (Fig. 1), the water footprint of BECCS would decrease from 575 m^3/tonne CO_2 to 333 m^3/tonne CO_2. This in turn would reduce global CCS water consumption from 5085–8564 km^3 to 3000–4900 km^3 under a 1.5 °C climate scenario by 2100.

4. Discussion

4.1. Trade-offs between water resources and climate mitigation

Building on previous efforts that assessed the water footprint of anthropogenic activities [9,93], this study quantifies the water footprint of four prominent CCS technologies in the context of stringent climate change mitigation. The need to decarbonize the global economy has led to an increasing interest in CCS as a climate mitigation strategy from a policy-making perspective [8,23,94,95]. At the same time, concerns have been arisen about their sustainability and the impacts on water and land use, energy needs and ecosystems [8]. In particular, the adoption of CCS technologies will likely increase demand for water. We analyze the water footprint of future CCS deployment both for low-carbon energy generation and direct carbon dioxide removal from the atmosphere, which both play a large role in stringent climate change mitigation.

We show that the water footprint of CCS varies with technology and that some technologies remove CO_2 in a more water-efficient way than others. While, BECCS has the highest water footprint, DACCS is the most water efficient technology to directly remove CO_2 from the atmosphere (Fig. 2). However, BECCS mostly uses green water while DACCS uses exclusively blue water and therefore may compete with municipal and industrial uses as well as irrigated agriculture. Conversely, green water uses for BECCS compete with agro-ecosystems for the use of land and associated rainwater needed for biomass production. Among the CCS technologies suitable for low carbon electricity production, oxy-combustion is the process with the lowest water footprint. We also illustrate the projected water requirements of the widespread adoption of CCS that is required to meet climate targets, considering a combination of CCS adoption scenarios (Fig. 5) and find that a diversified portfolio of CCS technologies is likely to have lower impacts on water resources than a scenario relying mainly on one technology, such as BECCS. Our results enable a more comprehensive understanding of water uses by the most prominent CCS technologies and can better inform management and policy decisions to identify the most effective use of water resources in meeting climate goals.

4.2. Biomass plantations and water resources

BECCS has the highest water footprint among CCS technologies and it is by far the process that will have greater impacts on global water consumption, accounting for more than 97% of the total water footprint

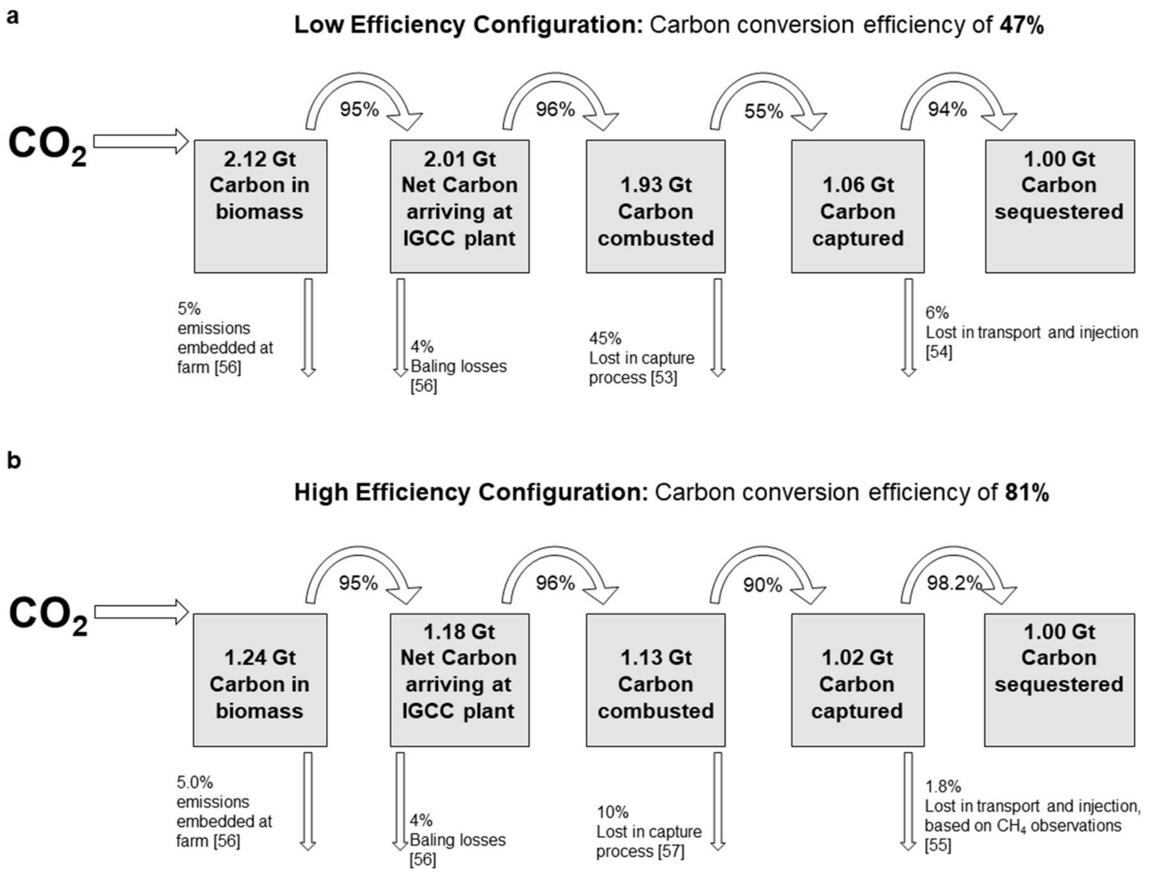


Fig. 1. BECCS carbon supply chain in low and high efficiency configurations. The percentage values are carbon losses from literature.

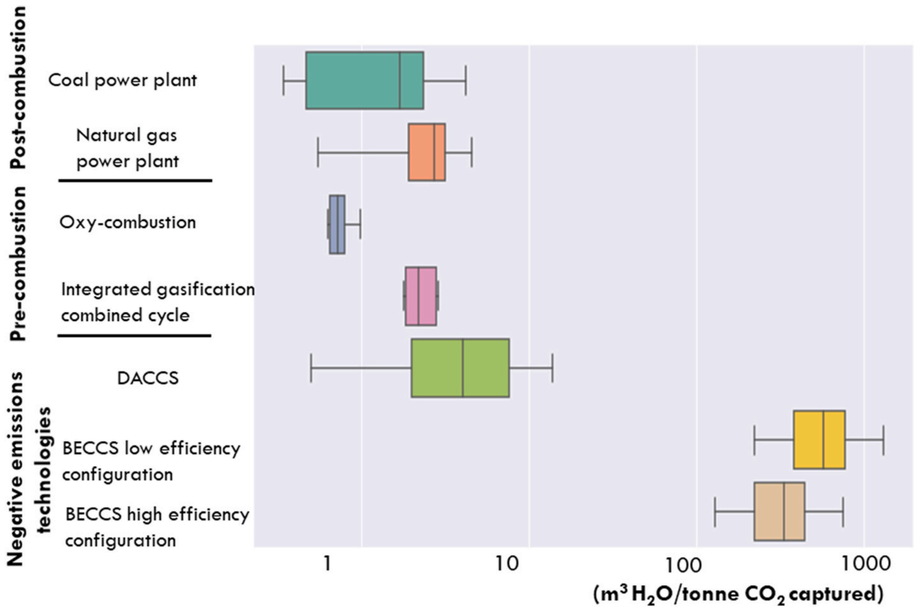


Fig. 2. The water footprint of carbon capture and storage technologies. The boxplots reports a range of water footprints of post-combustion CCS, pre-combustion CCS, and negative emission technologies. The water footprint of BECCS is shown for the low and high efficiency configurations (see Fig. 1). The boxplots represent median, 25th and 75th percentile, and maximum and minimum values of water footprint among the ensemble, outliers are not shown in the figure. Note one cubic meter of water is equal to one tonne of water.

from CCS technologies by 2100 (Fig. 5). Here assume that BECCS feedstock consume solely green water resources. However, under irrigated condition or in the case of phreatophyte vegetation, blue water can also be used by biomass plantation. In fact, cheap blue water from the Columbia River in Oregon has been used to irrigate biomass plantations [96]. Irrigation will likely be deployed to increase yields in biomass plantations [97] and therefore reduce the large land footprint that would be needed to meet climate targets through BECCS [98]. In addition, feedstock plantations could also have impacts on downstream blue water resources [99] when tree plantations act as phreatophytes and tap blue water from shallow aquifers to sustain their high evapotranspiration rates. For example, eucalyptus trees have shown the ability to take up blue water from the underneath aquifers and deplete blue water availability for downstream users [100–102]. Of great concern is

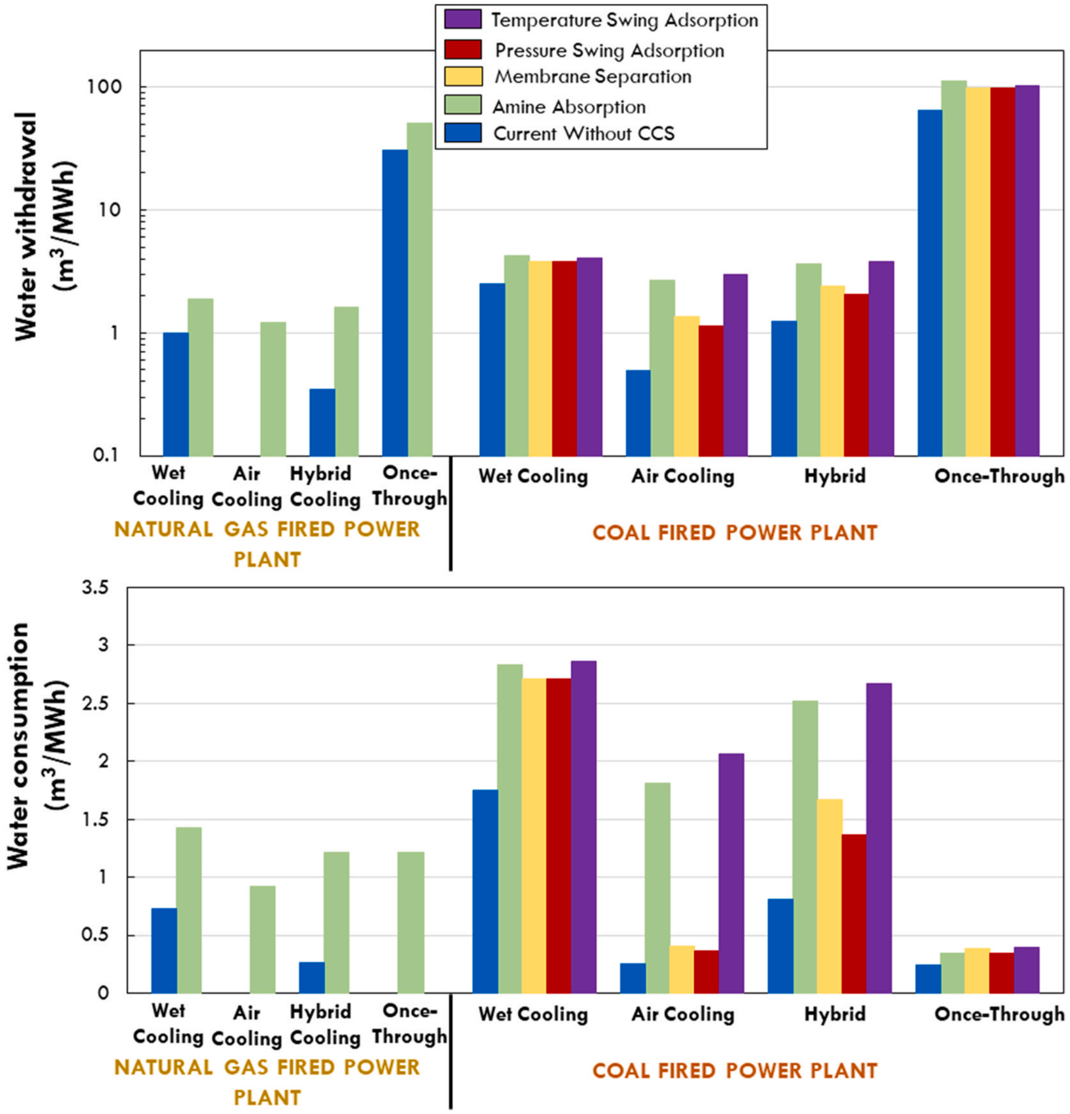


Fig. 3. Water consumption and withdrawal intensities of coal-fired and natural gas-fired plants with and without post-combustion CCS. There are four prominent post-combustion CCS technologies: amine absorption, pressure swing adsorption, pressure swing adsorption, and membrane separation. Despite amine absorption is proven and commercially available, membrane separation and adsorption post-combustion CCS systems are still at lower stages of development [3]. The figure was generated running the Integrated Environmental Control Model (IECM Version 11.2) [43] and considering a different range of air temperatures, relative humidity, and gross power inputs. Note that water withdrawal intensity is shown using a logarithmic scale.

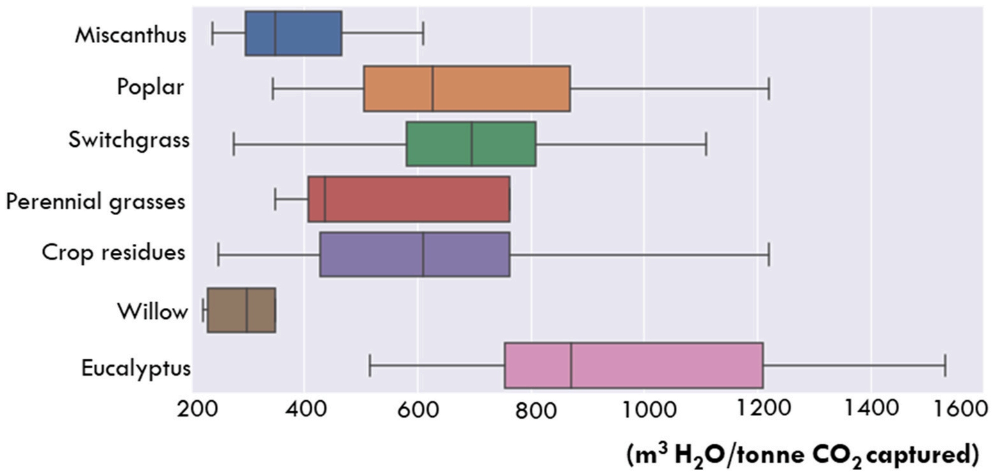


Fig. 4. The water footprint of dedicated BECCS feedstock. The figure was generated considering feedstock-specific water use efficiencies from previous studies (Table 1) and a BECCS carbon conversion efficiency equal to 47% (Fig. 1a). The figure shows green and blue water footprint. Because we do not assume that dedicated feedstock are irrigated, here, blue water for BECCS comes solely from the integrated gasification combined cycle process and it is equal to 0.74 m^3/tonne CO_2 (Fig. 2). The boxplots represent median, 25th and 75th percentile, and maximum and minimum values of water footprint among the ensemble of data collected, outliers are not shown in the figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

also the planting of large swaths of non-native tree species, many of which perish because their water needs are too great for local climate conditions [12]. Moreover, high CO_2 concentration in the atmosphere [103] and future technological development [104] will likely increase the efficiency and productivity of photosynthesis in crop plants, potentially reducing the water footprint of biomass plantations. C4 plants (corn, sorghum) will have higher water use efficiency than C3 crops [105]. Importantly, biomass plantations are likely to have other environmental liabilities in addition to impacts on water resources, such as nitrogen leakage, soil carbon and phosphorus loss, land use, albedo, and local climate change [8,50,106].

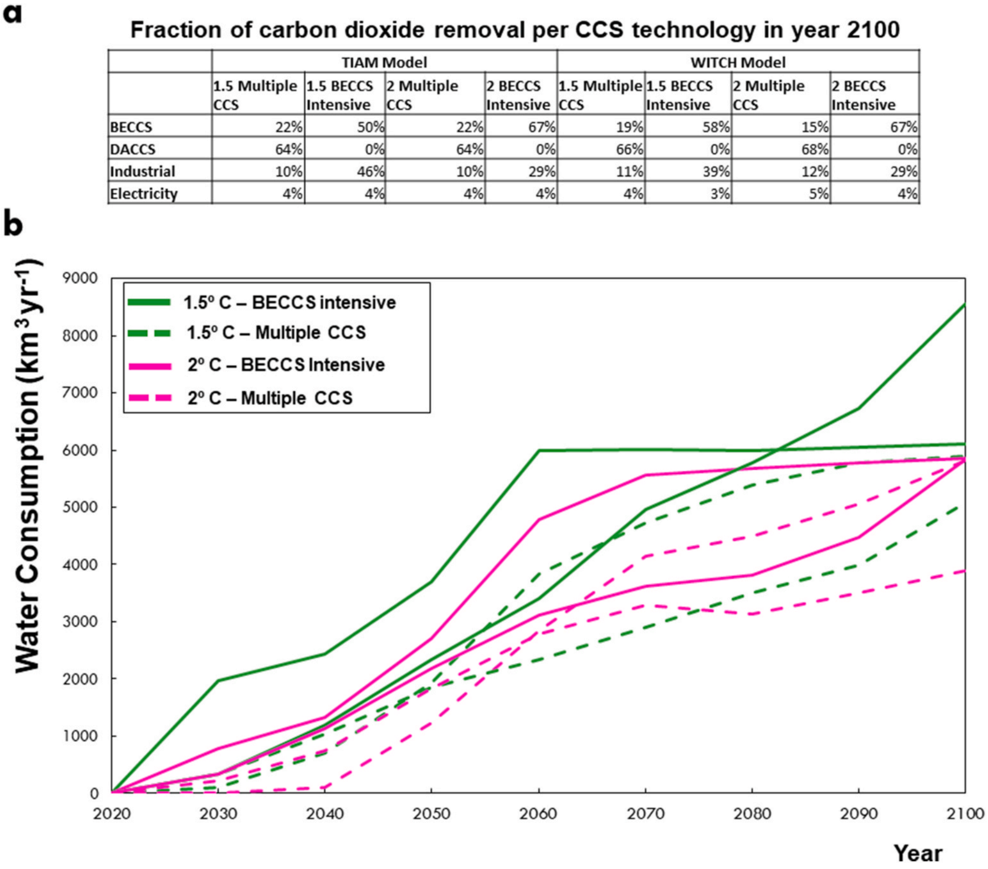
4.3. CCS and water planetary boundary

In some regions of the world, CCS adoption will likely put under additional stress freshwater resources that are already depleted, challenging water systems, rising concerns about water scarcity [107] and the Earth's ability to meet the water needs of humanity with its limited freshwater resources [21]. While, globally, the water footprint of humanity has not surpassed the planetary boundary of freshwater [108], societal water consumption is locally unsustainable in many regions worldwide. In fact, it has been estimated that 50% of blue water consumption [109] and 18% of green water consumption [110] overshoots maximum sustainable level for local green and blue water resources. An increase in water demand due to CCS deployment would draw humanity closer to the planetary boundary for both blue water [111] and green water [110], which are estimated to be 2800 km^3 yr^{-1} and 18,000 km^3 yr^{-1}, respectively (Fig. 6). We find that CCS adoption would increase by 84 (±56) km^3 yr^{-1} the current blue water consumption of humanity, which is estimated to be 1700 km^3 yr^{-1} [112]. CCS adoption – through BECCS – would require an additional 6757 (±1803) km^3 yr^{-1} of green water from the current green water consumption estimated to be 8720 km^3 yr^{-1} [110], or approximately 10% of global total evapotranspiration [113,114]. Therefore, CCS may increase competition for freshwater resources with other human activities such as the agricultural, industrial, and domestic sectors [109,115,116] and generate unsustainable conditions for freshwater ecosystems [117]. Green water appears to be the primary concern, as BECCS plantations will likely draw humanity closer to the planetary boundary for green water and generate widespread green water scarcity.

4.4. CCS and local water scarcity

Water is a local resource and the planetary boundaries for water need to be calculated starting from a local water balance assessment. Differently, carbon budgets are defined on a global scale, as the impact of carbon emissions on climate change does not depend on their specific location, but on the global CO_2 concentrations. In the case of CCS technologies, the exact location where these systems will likely be deployed remains unknown. Our study does not investigate the impacts of CCS technologies on local water availability and water scarcity. We, here, calculate the global amount of water resources that will be claimed by CCS technologies to meet stringent climate targets. Therefore, planning for CCS mitigation strategies for climate change should account for local water availability and the patterns of blue and green water scarcity [107].

We posit that the additional water consumption from CCS could strongly affect the local and global water resources exacerbating and creating widespread green and blue water scarcity conditions worldwide. For example, Rosa et al., 2020 [26] estimated that 23% of global coal plant capacity would face longer periods of blue water scarcity if retrofitted with post-combustion CCS. It is therefore fundamental to



Fraction of carbon dioxide removal per CCS technology in year 2100

	TIAM Model				WITCH Model			
	1.5 Multiple CCS	1.5 BECCS Intensive	2 Multiple CCS	2 BECCS Intensive	1.5 Multiple CCS	1.5 BECCS Intensive	2 Multiple CCS	2 BECCS Intensive
BECCS	22%	50%	22%	67%	19%	58%	15%	67%
DACCS	64%	0%	64%	0%	66%	0%	68%	0%
Industrial	10%	46%	10%	29%	11%	39%	12%	29%
Electricity	4%	4%	4%	4%	4%	3%	5%	4%

Fig. 5. Global yearly water consumption from CCS in the 21st century in a 1.5°C and 2°C consistent scenarios. The figure shows the water consumption required to achieve climate targets across different mitigation pathways. All pathways require carbon dioxide removal through CCS technologies, but the amount varies across climate scenarios, as do the relative contribution of post-combustion CCS, pre-combustion CCS, BECCS, and DACCS. This has implications for projected water consumption from CCS adoption. Projected carbon dioxide removal scenarios come from TIAM and WITCH integrated assessment models [33]. Panel a shows the share of carbon dioxide removal per technology in year 2100 [33]. Water consumption estimates were generated considering a BECCS carbon conversion efficiency equal to 47% (Fig. 1a).

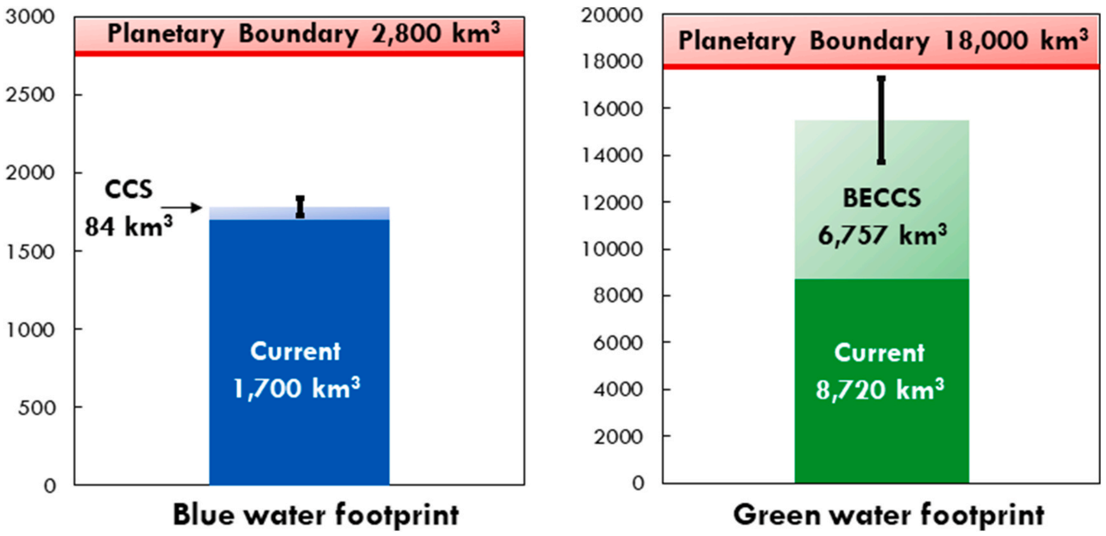


Fig. 6. Estimates of green and blue water footprints relative to proposed planetary boundaries. Bars show current and CCS green and blue water footprints. Blue water footprint from CCS is from expected adoption of pre-combustion, post-combustion, and DACCS in year 2100 under 1.5 °C climate scenarios. Green water footprint from CCS is from BECCS in year 2100 under 1.5 °C climate scenarios. The error bar ranges represent the uncertainty range of consumption use of blue water and green water from different carbon dioxide removal scenarios [33]. The figure was generated considering a BECCS carbon conversion efficiency equal to 47% (Fig. 1a). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

deploy CCS at those facilities not to be impacted by blue water scarcity. Appropriate plantations for biomass production to be used as feedstock in BECCS systems should be as well planned only in areas not to be affected by green water scarcity so as not to require irrigation.

5. Conclusions

Water scarcity is progressively perceived as a socio-environmental threat that could constrain anthropogenic activities and impair ecosystems. Water is also becoming an increasingly vexing factor in managing climate mitigation technologies such as carbon capture and storage. What is the global water footprint of carbon capture and storage under stringent climate change mitigation policy? We provide an answer to this question in the context of the four prominent CCS technologies. We estimate that to meet the 1.5 °C climate target, CCS would almost double the water footprint of humanity. Our results show that the water footprint of CCS strongly vary with technology. Some CCS technologies, however, consume much less water than others, suggesting that with appropriate decision it is possible to capture CO_2 in the most water-efficient way. Green water appears to be the primary concern, as BECCS plantations will likely draw humanity closer to the planetary boundary for green water and generate widespread green water scarcity. Our results show that a diversified portfolio with different CCS technologies and balanced strategies of mitigation and carbon removal will likely have lower water requirements than a portfolio relying mainly on one technology.

This study quantified the water footprint of carbon capture and storage technologies. We showed that CCS adoption necessarily entails large water requirements, and that different CCS processes have different water requirements to capture carbon dioxide. BECCS has the highest water footprint among CCS technologies and it is by far the process that will have greater impacts on global water consumption, particularly green water. There are already reasons of profound concern about whether the future food, energy, and fiber needs can be met using the limited freshwater resources of the Planet. The projected water requirements from CCS are of paramount concern and should be accounted for in the development of future climate policies. The results of this study can thus form an important basis for further assessments of how climate mitigation policies may increase the water footprint of humanity in the coming decades. Future research is required to reduce the water footprint of CCS processes and minimize the competition for the scarce freshwater resources of the Planet. The assessment of the water footprint of a broad range of CCS technologies can generate well-informed policies aiming to capture CO_2 in the most water-efficient way. This study provides insights into how CCS adoption consistent with 1.5 °C and 2 °C climate policies will influence the water footprint of humanity in the 21st century. The results of this study underscore the importance of integrating water footprints of CCS in future climate and energy policies. Our analysis provides important insights into the hydrological consequences of widespread CCS adoption. We conclude that a water sustainability assessment should be made in siting carbon capture and storage technologies.

CRediT authorship contribution statement

Lorenzo Rosa: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing - original draft. **Daniel L. Sanchez:** Conceptualization, Supervision, Writing - review & editing. **Giulia Realmonte:** Data curation, Writing - review & editing. **Dennis Baldocchi:** Supervision, Writing - review & editing. **Paolo D'Odorico:** Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

L.R. was supported by The Ermenegildo Zegna Founder's Scholarship and the Horton AGU Hydrology Research Grant. P.D. was funded by the USDA Hatch Multistate project #W4190 capacity fund.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2020.110511.

References

[1] Luderer G, Vrontisi Z, Bertram C, Edelenbosch OY, Pietzcker RC, Rogelj J, De Boer HS, Drouet L, Emmerling J, Fricko O, Fujimori S. Residual fossil CO 2 emissions in 1.5–2 C pathways. Nat Clim Change 2018;8(7):626–33.

[2] Intergovernmental Panel on Climate Change (IPCC). Global warming of 1.5 ° C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. 2019.

[3] Bui M, et al. Carbon capture and storage (CCS): the way forward. Energy Environ Sci 2018;11(5):1062–176.

[4] Anderson CM, DeFries RS, Litterman R, Matson PA, Nepstad DC, Pacala S, Schlesinger WH, Shaw MR, Smith P, Weber C, Field CB. Natural climate solutions are not enough. Science 2019;363(6430):933–4.

[5] Schlesinger WH, Amundson R. Managing for soil carbon sequestration: let's get realistic. Global Change Biol 2019;25(2):386–9.

[6] Bellamy R, Geden O. Govern CO2 removal from the ground up. Nat Geosci 2019; 12(11):874–6.

[7] Edenhofer O, et al., editors. IPCC *climate change 2014: Mitigation of climate change*. Cambridge Univ. Press; 2014.

[8] Smith P, Davis SJ, Creutzig F, Fuss S, Minx J, Gabrielle B, Kato E, Jackson RB, Cowie A, Kriegler E, Van Vuuren DP. Biophysical and economic limits to negative CO 2 emissions. Nat Clim Change 2016;6(1):42–50.

[9] Gerbens-Leenes W, Hoekstra AY, van der Meer TH. The water footprint of bioenergy. Proc Natl Acad Sci Unit States Am 2009;106(25):10219–23.

[10] Mekonnen MM, Hoekstra AY, Thompson S. The blue water footprint of electricity from hydropower. Hydrol Earth Syst Sci 2012;16(1).

[11] Scherer L, Pfister S. Global water footprint assessment of hydropower99. Renewable Energy; 2016. p. 711–20.

[12] Chen J, John R, Sun G, Fan P, Henebry GM, Fernández-Giménez ME, Zhang Y, Park H, Tian L, Groisman P, Ouyang Z. Prospects for the sustainability of social-ecological systems (SES) on the Mongolian plateau: five critical issues. Environ Res Lett 2018;13(12):123004.

[13] Feng X, Fu B, Piao S, Wang S, Ciais P, Zeng Z, Lü Y, Zeng Y, Li Y, Jiang X, Wu B. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. Nat Clim Change 2016;6(11):1019–22.

[14] Wang L, D'Odorico P. Water limitations to large-scale desert agroforestry projects for carbon sequestration. Proc Natl Acad Sci Unit States Am 2019;116(50): 24925–6.

[15] Ge J, Pitman AJ, Guo W, Zan B, Fu C. Impact of revegetation of the Loess Plateau of China on the regional growing season water balance. Hydrol Earth Syst Sci 2020;24(2):515–33.

[16] International Energy Agency. World energy outlook 2016. 2016.

[17] Fricko O, Parkinson SC, Johnson N, Strubegger M, van Vliet MT, Riahi K. Energy sector water use implications of a 2 C climate policy. Environ Res Lett 2016;11 (3):034011.

[18] Miara A, Macknick JE, Vörösmarty CJ, Tidwell VC, Newmark R, Fekete B. Climate and water resource change impacts and adaptation potential for US power supply. Nat Clim Change 2017;7(11):793.

[19] Jin Y, Behrens P, Tukker A, Scherer L. Water use of electricity technologies: a global meta-analysis. Renew Sustain Energy Rev 2019;115:109391.

[20] Gao X, Zhao Y, Lu S, Chen Q, An T, Han X, Zhuo L. Impact of coal power production on sustainable water resources management in the coal-fired power energy bases of Northern China. Appl Energy 2019;250:821–33.

[21] Rockström J, Falkenmark M, Lannerstad M, Karlberg L. The planetary water drama: dual task of feeding humanity and curbing climate change. Geophys Res Lett 2012;39(15).

[22] D'Odorico P, Davis KF, Rosa L, Carr JA, Chiarelli D, Dell'Angelo J, Gephart J, MacDonald GK, Seekell DA, Suweis S, Rulli MC. The global food-energy-water nexus. Rev Geophys 2018;56(3):456–531.

[23] Fuss S, Canadell JG, Peters GP, Tavoni M, Andrew RM, Ciais P, Jackson RB, Jones CD, Kraxner F, Nakicenovic N, Le Quéré C. Betting on negative emissions. Nat Clim Change 2014;4(10):850–3.

[24] National Academies of Sciences, Engineering, and Medicine. Negative emissions Technologies and Reliable Sequestration: A Research Agenda. Washington, DC: The National Academies Press; 2019. https://doi.org/10.17226/25259.

[25] Fuhrman J, McJeon H, Patel P, Doney SC, Shobe WM, Clarens AF. Food–energy–water implications of negative emissions technologies in a+ 1.5 C future. Nat. Clim. Chang. 2020:1–8.

[26] Rosa L, Reimer JA, Went MS, D'Odorico P. Hydrological limits to carbon capture and storage. Nature Sustainability 2020:1–9.

[27] Zhai H, Rubin ES. Performance and cost of wet and dry cooling systems for pulverized coal power plants with and without carbon capture and storage. Energy Pol 2010;38(10):5653–60.

[28] Meldrum J, Nettles-Anderson S, Heath G, Macknick J. Life cycle water use for electricity generation: a review and harmonization of literature estimates. Environ Res Lett 2013;8(1):015031.

[29] Zhai H, Rubin ES, Versteeg PL. Water use at pulverized coal power plants with post-combustion carbon capture and storage. Environ Sci Technol 2011;45(6): 2479–85.

[30] Keith DW, Holmes G, Angelo DS, Heidel K. A process for capturing CO2 from the atmosphere. Joule 2018;2(8):1573–94.

[31] Stenzel F, Gerten D, Werner C, Jägermeyr J. Freshwater requirements of large-scale bioenergy plantations for limiting global warming to 1.5° C. Environ Res Lett 2019;14(8):084001.

[32] Mielke E, Anadon LD, Narayanamurti V. Water consumption of energy resource extraction, processing, and conversion. Belfer Center for Science and International Affairs; 2010.

[33] Realmonte G, Drouet L, Gambhir A, Glynn J, Hawkes A, Köberle AC, Tavoni M. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nat Commun 2019;10(1):3277.

[34] Hoekstra AY. The water footprint of modern human societies. second ed. London: EarthScan; 2020.

[35] Hogeboom RJ. The Water Footprint Concept and Water's Grand Environmental Challenges. One Earth 2020;2(3):218–22.

[36] Gambhir A, Tavoni M. Direct air carbon capture and sequestration: how it works and how it could contribute to climate-change mitigation. One Earth 2019;1(4): 405–9.

[37] Fasihi M, Efimova O, Breyer C. Techno-economic assessment of CO2 direct air capture plants. J Clean Prod 2019;224:957–80.

[38] Sandalow D, Friedmann J, McCormick C. Direct Air Capture of Carbon Dioxide: ICEF Roadmap. 2018. https://www.icef-forum.org/pdf2018/roadmap/ICEF2018_Roadmap_Dra_for_Comment_20181012.pdf.

[39] Sanchez DL, Johnson N, McCoy ST, Turner PA, Mach KJ. Near-term deployment of carbon capture and sequestration from biorefineries in the United States. Proc Natl Acad Sci Unit States Am 2018;115(19):4875–80.

[40] Sanchez DL, Zimring T, Mater C, Harrell K, et al. Literature review and evaluation of research gaps to support wood products innovation. Technical Report of the Board of Forestry and Fire Protection Joint Institute for Wood Products Innovation 2020. https://bof.fire.ca.gov/media/9688/full-12-a-jiwpi_formattedv12_3_05_2020.pdf. [Accessed 26 October 2020].

[41] Leung DY, Caramanna G, Maroto-Valer MM. An overview of current status of carbon dioxide capture and storage technologies. Renew Sustain Energy Rev 2014;39:426–43.

[42] Smit B, Reimer JA, Oldenburg CM, Bourg IC. Introduction to Carbon Capture and Sequestration. 2014 [London].

[43] Integrated Environmental Control Model (IECM). Integrated environmental Control model computer code and documentation. Available at, https://www.cmu.edu/epp/iecm/iecm_dl.html; 2009.

[44] Zhai H, Rubin ES. Water impacts of a low-carbon electric power future: assessment methodology and status. Current Sustainable/Renewable Energy Reports 2015;2(1):1–9.

[45] Socolow R, Desmond M, Aines R, Blackstock J, Bolland O, Kaarsberg T, Lewis N, Mazzotti M, Pfeffer A, Sawyer K, Siirola J. *Direct air capture of CO2 with chemicals: a technology assessment for the APS Panel on Public Affairs* (No. BOOK). American Physical Society; 2011.

[46] Sinclair TR, Tanner CB, Bennett JM. Water-use efficiency in crop production. Bioscience 1984;34(1):36–40.

[47] Hatfield JL, Dold C. Water-use efficiency: advances and challenges in a changing climate. Front Plant Sci 2019;10.

[48] Tang X, Li H, Desai AR, Nagy Z, Luo J, Kolb TE, Olioso A, Xu X, Yao L, Kutsch W, Pilegaard K. How is water-use efficiency of terrestrial ecosystems distributed and changing on Earth? Sci Rep 2014;4:7483.

[49] Eichelmann E, Wagner-Riddle C, Warland J, Deen B, Voroney P. Comparison of carbon budget, evapotranspiration, and albedo effect between the biofuel crops switchgrass and corn231. Agriculture, Ecosystems & Environment; 2016. p. 271–82.

[50] Baldocchi D, Penuelas J. The physics and ecology of mining carbon dioxide from the atmosphere by ecosystems. Global Change Biol 2019;25(4):1191–7.

[51] Stoy PC, El-Madany TS, Fisher JB, Gentine P, Gerken T, Good SP, Klosterhalfen A, Liu S, Miralles DG, Perez-Priego O, Rigden AJ. Reviews and syntheses: turning the challenges of partitioning ecosystem evaporation and transpiration into opportunities. Biogeosciences 2019;16(19):3747–75.

[52] Smith LJ, Torn MS. Ecological limits to terrestrial biological carbon dioxide removal. Climatic Change 2013;118(1):89–103.

[53] Rhodes JS, Keith DW. Engineering economic analysis of biomass IGCC with carbon capture and storage. Biomass Bioenergy 2005;29(6):440–50.

[54] Weisser D. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. Energy 2007;32(9):1543–59.

[55] Brandt AR, Heath GA, Kort EA, O'Sullivan F, Pétron G, Jordaan SM, Tans P, Wilcox J, Gopstein AM, Arent D, Wofsy S. Methane leaks from North American natural gas systems. Science 2014;343(6172):733–5.

[56] Qin X, Mohan T, El-Halwagi M, Cornforth G, McCarl BA. Switchgrass as an alternate feedstock for power generation: an integrated environmental, energy and economic life-cycle assessment. Clean Technol Environ Policy 2006;8(4): 233–49.

[57] Greenhouse Gas Reductions in the Power Industry Using Domestic Coal and Biomass: Volume 1: IGCC (National Energy Technology Laboratory, 2012).

[58] Reich PB, Lassoie JP. Effects of low level O3 exposure on leaf diffusive conductance and water-use efficiency in hybrid poplar. Plant Cell Environ 1984;7 (9):661–8.

[59] Ripullone F, Lauteri M, Grassi G, Amato M, Borghetti M. Variation in nitrogen supply changes water-use efficiency of Pseudotsuga menziesii and Populus x euroamericana; a comparison of three approaches to determine water-use efficiency. Tree Physiol 2004;24(6):671–9.

[60] Wang C, Liu S, Dong Y, Zhao Y, Geng A, Xia X, Yin W. Pd EPF 1 regulates water-use efficiency and drought tolerance by modulating stomatal density in poplar. Plant biotechnology journal 2016;14(3):849–60.

[61] Xin Z, Aiken R, Burke J. Genetic diversity of transpiration efficiency in sorghum. Field Crop Res 2009;111(1–2):74–80.

[62] Fischer M, Trnka M, Kučera J, Fajman M, Žalud Z. Biomass productivity and water use relation in short rotation poplar coppice (Populus nigra x P. maximowiczii) in the conditions of Czech Moravian Highlands. Acta Univ Agric Silvic Mendelianae Brunensis 2014;59(6):141–52.

[63] Foti S, Cosentino S. Colture erbacee annuali e poliennali da energia. Riv Agron 2001;35:200–15.

[64] Cosentino SL, Patane C, Sanzone E, Copani V, Foti S. Effects of soil water content and nitrogen supply on the productivity of Miscanthus× giganteus Greef et Deu. in a Mediterranean environment. Ind Crop Prod 2007;25(1):75–88.

[65] Mantineo M, D'agosta GM, Copani V, Patanè C, Cosentino SL. Biomass yield and energy balance of three perennial crops for energy use in the semi-arid Mediterranean environment. Field Crop Res 2009;114(2):204–13.

[66] Zhuang Q, Qin Z, Chen M. Biofuel, land and water: maize, switchgrass or Miscanthus? Environ Res Lett 2013;8(1):015020.

[67] Triana F, Nassi o Di Nasso N, Ragaglini G, Roncucci N, Bonari E. Evapotranspiration, crop coefficient and water use efficiency of giant reed (Arundo donax L.) and miscanthus (Miscanthus× giganteus Greef et Deu.) in a Mediterranean environment. Gcb Bioenergy 2015;7(4):811–9.

[68] Zeri M, Hussain MZ, Anderson-Teixeira KJ, DeLucia E, Bernacchi CJ. Water use efficiency of perennial and annual bioenergy crops in central Illinois. J Geophys Res: Biogeosciences 2013;118(2):581–9.

[69] Kørup K, Lærke PE, Baadsgaard H, Andersen MN, Kristensen K, Münnich C, Didion T, Jensen ES, Mårtensson LM, Jørgensen U. Biomass production and water use efficiency in perennial grasses during and after drought stress. Gcb Bioenergy 2018;10(1):12–27.

[70] Mueller L, Behrendt A, Schalitz G, Schindler U. Above ground biomass and water use efficiency of crops at shallow water tables in a temperate climate. Agric Water Manag 2005;75(2):117–36.

[71] Eichelmann E, Wagner-Riddle C, Warland J, Deen B, Voroney P. Evapotranspiration, water use efficiency, and energy partitioning of a mature switchgrass stand. Agric For Meteorol 2016;217:108–19.

[72] Li C. Population differences in water-use efficiency of Eucalyptus microtheca seedlings under different watering regimes. Physiol Plantarum 2000;108(2): 134–9.

[73] Stape JL, Binkley D, Ryan MG. Eucalyptus production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. For Ecol Manag 2004;193(1–2):17–31.

[74] Akhter J, Mahmood K, Tasneem MA, Malik KA, Naqvi MH, Hussain F, Serraj R. Water-use efficiency and carbon isotope discrimination of Acacia ampliceps and Eucalyptus camaldulensis at different soil moisture regimes under semi-arid conditions. Biol Plantarum 2005;49(2):269–72.

[75] Forrester DI, Theiveyanathan S, Collopy JJ, Marcar NE. Enhanced water use efficiency in a mixed Eucalyptus globulus and Acacia mearnsii plantation. For Ecol Manag 2010;259(9):1761–70.

[76] Hubbard RM, Stape J, Ryan MG, Almeida AC, Rojas J. Effects of irrigation on water use and water use efficiency in two fast growing Eucalyptus plantations. For Ecol Manag 2010;259(9):1714–21.

[77] Xu B, Li F, Shan L, Ma Y, Ichizen N, Huang J. Gas exchange, biomass partition, and water relationships of three grass seedlings under water stress. Weed Biol Manag 2006;6(2):79–88.

[78] VanLoocke A, Twine TE, Zeri M, Bernacchi CJ. A regional comparison of water use efficiency for miscanthus, switchgrass and maize. Agric For Meteorol 2012; 164:82–95.

[79] Yimam YT, Ochsner TE, Kakani VG. Evapotranspiration partitioning and water use efficiency of switchgrass and biomass sorghum managed for biofuel. Agric Water Manag 2015;155:40–7.

[80] Halldin S. Willow stand evaporation: simulation of diurnal distribution using synoptic weather data. In: Perttu KL, Kowalik PJ, editors. Modelling of energy forestry: growth, water relations and economics. Simulation monograph No. 30. Wageningen: Pudoc; 1989. p. 121. 146.

[81] Linderson ML, Iritz Z, Lindroth A. The effect of water availability on stand-level productivity, transpiration, water use efficiency and radiation use efficiency of field-grown willow clones. Biomass Bioenergy 2007;31(7):460–8.

[82] Lindroth A, Verwijst T, Halldin S. Water-use efficiency of willow: variation with season, humidity and biomass allocation. J Hydrol 1994;156(1–4):1–19.

[83] Bosetti V, Carraro C, Galeotti M, Massetti E, Tavoni M. A world induced technical change hybrid model (Special Issue# 2) Energy J 2006.

[84] Loulou R, Labriet M. ETSAP-TIAM: the TIMES integrated assessment model Part I: model structure. Comput Manag Sci 2008;5(1–2):7–40.

[85] Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V, Vilariño MV. Mitigation pathways compatible with 1.5°C in the context of sustainable development. In: Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla PR, Waterfield T, editors. Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Geneva, Switzerland: Intergovernmental Panel on Climate Change; 2018. p. 313–443.

[86] Hejazi MI, Voisin N, Liu L, Bramer LM, Fortin DC, Hathaway JE, Huang M, Kyle P, Leung LR, Li HY, Liu Y. 21st century United States emissions mitigation could increase water stress more than the climate change it is mitigating. Proc Natl Acad Sci Unit States Am 2015;112(34):10635–40.

[87] Tong D, Zhang Q, Zheng Y, Caldeira K, Shearer C, Hong C, Qin Y, Davis SJ. Committed emissions from existing energy infrastructure jeopardize 1.5 C climate target. Nature 2019;572(7769):373–7.

[88] Davis SJ, Lewis NS, Shaner M, Aggarwal S, Arent D, Azevedo IL, Benson SM, Bradley T, Brouwer J, Chiang YM, Clack CT. Net-zero emissions energy systems. Science 2018;360(6396):eaas9793.

[89] Kätelhön A, Meys R, Deutz S, Suh S, Bardow A. Climate change mitigation potential of carbon capture and utilization in the chemical industry. Proc Natl Acad Sci Unit States Am 2019;116(23):11187–94.

[90] Siegelman RL, Milner PJ, Kim EJ, Weston SC, Long JR. Challenges and opportunities for adsorption-based CO 2 capture from natural gas combined cycle emissions. Energy Environ Sci 2019;12(7):2161–73.

[91] Minx JC, Lamb WF, Callaghan MW, Fuss S, Hilaire J, Creutzig F, Amann T, Beringer T, de Oliveira Garcia W, Hartmann J, Khanna T. Negative emissions—Part 1: research landscape and synthesis. Environ Res Lett 2018;13 (6):063001.

[92] Rogelj J, Popp A, Calvin KV, Luderer G, Emmerling J, Gernaat D, Fujimori S, Strefler J, Hasegawa T, Marangoni G, Krey V. Scenarios towards limiting global mean temperature increase below 1.5 C. Nat Clim Change 2018;8(4):325.

[93] Hoekstra AY, Mekonnen MM. The water footprint of humanity. Proc Natl Acad Sci Unit States Am 2012;109(9):3232–7.

[94] Renforth P, Wilcox J. The role of negative emission technologies in addressing our climate goals. Frontiers in Climate 2020;2:1.

[95] Friedmann SJ. Engineered CO2 removal,. Climate restoration, and humility. Frontiers in Climate 2019;1:3.

[96] Spinelli R, Hartsough BR. Harvesting SRF poplar for pulpwood: experience in the pacific northwest. Biomass Bioenergy 2006;30(5):439–45.

[97] Stenzel F, Gerten D, Hanasaki N. Global scenarios of irrigation water use for bioenergy production: a systematic review. Hydrol Earth Syst Sci Discuss 2020: 1–24.

[98] Harper AB, Powell T, Cox PM, House J, Huntingford C, Lenton TM, Sitch S, Burke E, Chadburn SE, Collins WJ, Comyn-Platt E. Land-use emissions play a critical role in land-based mitigation for Paris climate targets. Nat Commun 2018; 9(1):1–13.

[99] Chiarelli DD, Passera C, Rulli MC, Rosa L, Ciraolo G, D'Odorico P. Hydrological consequences of natural rubber plantations in Southeast Asia. Land Degrad. Dev. 2020;31(15):2060–73.

[100] Allison GB, Cook PG, Barnett SR, Walker GR, Jolly ID, Hughes MW. Land clearance and river salinisation in the western Murray Basin, Australia. J Hydrol 1990;119(1–4):1–20.

[101] George RJ, Nulsen RA, Ferdowsian R, Raper GP. Interactions between trees and groundwaters in recharge and discharge areas–A survey of Western Australian sites. Agric Water Manag 1999;39(2–3):91–113.

[102] Jobbágy EG, Jackson RB. Groundwater and soil chemical changes under phreatophytic tree plantations. J Geophys Res: Biogeosciences 2007;112(G2).

[103] Liberloo M, Calfapietra C, Lukac M, Godbold D, LUO ZB, Polle A, Hoosbeek MR, Kull O, Marek M, Raines C, Rubino M. Woody biomass production during the second rotation of a bio-energy Populus plantation increases in a future high CO2 world. Global Change Biol 2006;12(6):1094–106.

[104] Ort DR, Merchant SS, Alric J, Barkan A, Blankenship RE, Bock R, Croce R, Hanson MR, Hibberd JM, Long SP, Moore TA. Redesigning photosynthesis to sustainably meet global food and bioenergy demand. Proc Natl Acad Sci Unit States Am 2015;112(28):8529–36.

[105] Ehleringer J, Cerling T, Helliker B. C4 photosynthesis, atmospheric CO2, and climate, vol. 112. Oecologia; 1997.

[106] Robertson GP, Hamilton SK, Del Grosso SJ, Parton WJ. The biogeochemistry of bioenergy landscapes: carbon, nitrogen, and water considerations. Ecol Appl 2011;21(4):1055–67.

[107] Rosa L, Chiarelli DD, Rulli MC, Dell'Angelo J, D'Odorico P. Global agricultural economic water scarcity. Science Advances 2020;6:eaaz6031.

[108] Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, Biggs R, Carpenter SR, De Vries W, De Wit CA, Folke C. Planetary boundaries: guiding human development on a changing planet. Science 2015;347(6223):1259855.

[109] Rosa L, Chiarelli DD, Tu C, Rulli MC, D'Odorico P. Global unsustainable virtual water flows in agricultural trade. Environ Res Lett 2019;14(11):114001.

[110] Schyns JF, Hoekstra AY, Booij MJ, Hogeboom RJ, Mekonnen MM. Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy. Proc Natl Acad Sci Unit States Am 2019;116(11):4893–8.

[111] Gerten D, Hoff H, Rockström J, Jägermeyr J, Kummu M, Pastor AV. Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements. Current Opinion in Environmental Sustainability 2013;5(6):551–8.

[112] Qin Y, Mueller ND, Siebert S, Jackson RB, AghaKouchak A, Zimmerman JB, Tong D, Hong C, Davis SJ. Flexibility and intensity of global water use. Nature Sustainability 2019;2(6):515–23.

[113] Ryu Y, Baldocchi DD, Kobayashi H, van Ingen C, Li J, Black TA, Beringer J, Van Gorsel E, Knohl A, Law BE, Roupsard O. Integration of MODIS land and atmosphere products with a coupled-process model to estimate gross primary productivity and evapotranspiration from 1 km to global scales. Global Biogeochem Cycles 2011;25(4).

[114] Trenberth Kevin E, Fasullo John T, Jeffrey Kiehl. Earth's global energy budget. Bull Am Meteorol Soc 2009;90:311–23.

[115] Flörke M, Schneider C, McDonald RI. Water competition between cities and agriculture driven by climate change and urban growth. Nature Sustainability 2018;1(1):51–8.

[116] Rosa L, Rulli MC, Davis KF, Chiarelli DD, Passera C, D'Odorico P. Closing the yield gap while ensuring water sustainability. Environ Res Lett 2018;13(10):104002.

[117] Jägermeyr J, Pastor A, Biemans H, Gerten D. Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation. Nat Commun 2017;8(1):1–9.