Desalinated Irrigation as a Sustainable and Renewable Source of Water Security for Future Agriculture

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Abstract

Agriculture is under significant pressure to meet current and future food demands. Food consumption growth and climate change push the system to produce more food with the same resources. Irrigation is a key strategy to producing higher yields but current practices are already consuming non-renewable water, threatening the natural and human ecosystem. Desalination – the conversion of saltwater from to freshwater – could help ease constraints on irrigation resources, eliminate unsustainable withdrawals and improve yields in a more difficult climate for food producers (for example in increasingly drier regions). However the extent to which desalination can be deployed, and its associated impacts at a global level is largely unquantified. Using data from 172 countries, We estimate the global demand for desalinated irrigation water in 2050 accounting for climate change and varying blue water availability. We assume this water is used to replace both unsustainably sourced freshwater and to meet irrigation requirements under climatic changes. We assess its cost, energy requirement and the brine produced (an environmental impact from desalination). Results indicate that desalinated water could sustainably feed an additional 500 million to 1 billion people when replacing unsustainable blue water withdrawals within the current system and up to 3.5-5 billion people when providing the water resources to close yield gaps. The annual cost of water is significantly higher than current irrigation at 160-2000 billion euros. The use of desalination at a global scale is unlikely due to prohibitive costs and energy requirements. The feasibility of desalination increases with future technological advancements, increasing water scarcity, decreasing costs, and renewable energy integration. However, challenges such as brine disposal and socio-economic constraints need to be solved. We anticipate that desalinated irrigation is looked at as a niche pathway to provide necessary water resources next to storage fed irrigation and irrigation water application efficiency improvements.

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Introduction

Agriculture faces unprecedented challenges in responding to the rising demand for food. Drivers of increased demand are global population growth, wealth increases, and food consumption patterns pushing planetary boundaries (Beltran-Pena et al., 2020). The global population will increase from 8.1 to 9.7 billion people by 2050 (FAO, 2022). In stark contrast it is estimated that if planetary boundaries were strictly observed our agricultural system can only feed 3.4 billion people if they adhere to a balanced diet of 2335 kcal per person per day (Gerten et al., 2020). However, current estimates put the global average diet in 2050 between 3070 and 3177 kcal, a gross overshoot (Alexandratos & Bruinsma, 2012; Bodirsky et al., 2015). At the same time, climate change threatens vital production regions and, to a much lesser extent, trends in urbanisation can take land out of food production (Alexandratos & Bruinsma, 2012; Mahato, 2014; Tilman et al., 2011). Global demands need to be met sustainably to protect future generations. however current unsustainable agricultural practices deplete water resources, negatively impact water quality, change and impair the natural landscapes and are responsible for one third of anthropogenic GHG emissions (Crippa et al., 2021; Curtis et al., 2018; Elliott et al., 2014; Gleick & Palaniappan, 2010).

Increasing agricultural productivity and yields from the same amount of land is vital to provide enough food, irrigation is the key strategy to achieving this. Crop growth needs water, but rainfall (green water) is insufficient in many regions, limiting crop productivity and yields in two-thirds of rainfed agriculture (Elliott et al., 2014; Jägermeyr et al., 2017; Sauer et al., 2010). Climate change further affects these systems by changing rainfall patterns, temperatures and biodiversity loss exacerbate variability in rainfed yields (Irmak et al., 2022). Droughts and heatwaves compromise water quality, reducing oxygen contents and increasing water temperature, algae, salinity, and pollution. This negatively affects yields further (van Vliet et al., 2023; Wang et al., 2024)).

Irrigation provides a secure source of water for agriculture. Producers source blue water, through river diversion and groundwater pumping, from surface and groundwater to distribute on agricultural lands constrained by water. However, these withdrawals often exceed renewable blue water resources in the region. For example, the majority of countries in the Middle East and North Africa (MENA) region experience significant water stress: the ratio of water withdrawn to water available is near or over 100% of their renewable water resources and projected to increase further as population and food demand grow (Elliott et al., 2014; FAO, 2022; H. Ritchie & Roser, 2017). Water availability is often a constraining factor in crop productivity (Ali & Talukder, 2008; Davis et al., 2017; Lobell et al., 2009). Supplementing green water with blue water (irrigation) enables higher yields in many areas. Agriculture accounts for 70% of global blue water withdrawals (FAO, 2022). Globally 20% of agricultural lands are equipped for irrigation accounting for approximately 40% of all yields (D'Odorico et al., 2018).

To meet future needs, both changes in demand and supply would be needed. The amount of resources we consume can be reduced by preventing food waste and shifting to more sustainable diets (Gerten et al., 2020; Jalava et al., 2016). Supply expansion aided by irrigation can be done in two ways: extensification, creating new agricultural lands and intensification of existing agriculture (Foley et al., 2011). Both extensification and intensification are vital to ensuring the future of our food supply as key prerequisites for feeding our growing population are spatially redistributed cropland and improved water–nutrient management (Gerten et al., 2020). Extensification must be considered carefully as it can have consequences for the natural environment encroaching on natural lands adversely impacting habitats, biodiversity, and ecological systems, such as rainforests, vital for sustaining life on earth (Chaplin-Kramer et al., 2019; Runyan & D'Odorico, 2012; Silva Junior et al., 2021). Intensification of existing agriculture requires increased resources: primarily water, supplied by irrigation, and fertiliser. In the future it is likely that both pathways are needed to meet demand.

Yield gaps in agriculture are the difference between actual crop yield and maximum attainable crop yield (Lobell et al., 2009). Analysis suggests a doubling of current blue water withdrawals is required to close the yield gaps that currently exist (Beltran-Pena et al., 2020; Rosa et al., 2018). However, one third of current and half of the withdrawals when closing yield gaps are from unsustainable sources. Blue water consumption in large regions of the world exceeds renewable blue water supply (Mueller et al., 2012; Rosa et al., 2018). Research into the sustainable consumption of blue water shows 41% of consumption occurs at the expense of environmental flow requirements, detrimental to the ability of river systems to provide life supporting functions. More than half of irrigated areas are negatively impacted when these excessive withdrawals are halted resulting in 10-30% lower yields (Jägermeyr et al., 2017). Wasteful use of water is indicative of our current system; research suggests irrigation water is applied at only about 55% efficiency globally, raising requirements much higher than the biophysical requirements of crops (Hoogeveen et al., 2015). A move to sprinkler irrigation and drip irrigation could raise application efficiency to 70-95% (Fyles & Madramootoo, 2016; van der Kooij et al., 2013). This would significantly reduce the amount of water required in agriculture and address the problem at its roots. The best water to use from a systems perspective is wasted water.

Alongside efficiency improvements which reduce blue water use, research often considers constructing additional water storage infrastructure to increase blue water supply: it suggests that there are unstored blue water resources capable of feeding an additional 1.15 billion people (Rosa et al., 2020). However if the hypothetical maximum amount of future dams are constructed, only half of this underutilised water can be stored (Schmitt et al., 2022). Building more is in many cases not preferable due to negative effects such as: disruption of ecological systems, destruction of natural habitats, displacement of human population, large land concessions, and significant financial cost. Above all climate change exacerbates the issue of surface water quality, the same water that would be stored by dams, adversely affecting yields (Elliott et al., 2014; van Vliet et al., 2023)

An outside the box alternative to sourcing blue water through storage is to create it from salt water (Caldera & Breyer, 2020; Jones et al., 2019; Martínez-Alvarez et al., 2016). Where blue water demand exceeds its renewable availability creating the necessary water unconstrained by the blue water system is a promising prospect. As a resource, salt water is readily available globally as more than 99% of liquid water on earth is salt water (Musie & Gonfa, 2023). Today only 2% of desalinated water is used for irrigation, as costs per m3 have been prohibitive compared to fresh water which is still sufficiently abundant in large parts of the world (Eke et al., 2020; Ghaffour et al., 2013; Martínez-Alvarez et al., 2016). Sea water reverse osmosis (SWRO), membrane based separation, is the most promising desalination technology due to its low energy requirements and low costs.

The majority of current academic research on desalination is on this technology and its variants. It accounts for 30% of global capacity and is projected to increase rapidly in market share compared to older more energy intensive thermal separation methods. Improving technology, decreasing capital costs and energy requirements in combination with increasing water scarcity are driving its adoption (Ahmed et al., 2021; Caldera & Breyer, 2017, 2019; Eke et al., 2020; Ghazi et al., 2022; Jones et al., 2019; Park & Lee, 2022). The levelized cost of water (LCOW), encompassing both capital and operational expenditures of SWRO using renewable energy is estimated at 0.7 - 2 €/m3 in 2030, followed by a further decline to 0.45 - 1.7 €/m3 by 2050 (Caldera & Breyer, 2019, 2020). The range of costs can be large depending on the distance required to pump the water. Advancements in technology are projected to improve energy consumption and reduce brine production (Ahmed et al., 2021; Atia et al., 2021; Ghernaout, 2019)

When considering SWRO as a solution to our irrigation needs it is important that we consider what happens with its primary waste product. Brine is created in great quantities during the desalination process; it was estimated that for 1m3 of desalinated water 1.5 m3 of brine is produced. Brine disposal is a challenge to the expansion of desalination as a technology (Jones et al., 2019). Effective management of brine production is crucial, as improper disposal can lead to increased salinity in natural water bodies. Saline water is known to reduce crop yield therefore we must ensure it does not enter freshwater irrigation systems (Zörb et al., 2019). On the other hand the ability to control the salinity of water through water has shown to lead to increased yields and reduced water requirements in small scale testing (Martínez-Alvarez et al., 2016).

Here, we explore the global potential for supplementing blue water resources, specifically those consumed by agricultural irrigation through SWRO. We examine a future where desalinated water is used for irrigation at a scale much larger than currently employed. We explore the potential for desalination of irrigation water to eliminate current unsustainable practices and close yield gaps in 2050. We assess the renewable energy requirement, cost, and waste production of the projected desalination capacity. Our research contributes to the field of Industrial Ecology by exploring the use of desalinated water as a sustainable solution for agricultural irrigation and our global future food demand. By integrating renewable energy with desalinated irrigation, we address critical water scarcity challenges while minimising environmental impacts, which aligns with the core principles of industrial ecology. By understanding how desalinated irrigation can play a role in our future food system we further the ability to solve its systemic problems, a key aim of industrial ecology.

Methodology

We analyse the potential of desalinated irrigation water globally with data from 172 countries grouped into eight different regions: Middle East and North Africa, East Asia and Pacific, North America, Western Europe, Latin America and Caribbean, Southern Asia, Eastern Europe and Central Asia, Sub-Saharan Africa. We then focus on the potential for desalinated irrigation in 2050 and its associated energy use, cost of water, and brine production.

To find the volume of agriculture-related desalinated water required we must first establish how much desalinated water can effectively be used in irrigation. For this analysis, we assume that the amount of irrigation water required is equal to the amount needed to close the yield gap of a crop, given the current extent of agricultural lands. The availability of water is often a limiting factor in maximising yields (Ali & Talukder, 2008; Davis et al., 2017; Lobell et al., 2009). For our research we assume these yields are not constrained by fertilisation and soil fertility, social and economic factors, technological availability, and farming practices (Beza et al., 2017; Hillocks, 2014; Mueller et al., 2012; Snyder et al., 2016). This limits the scope of our studies, though local water availability is often the constraining factor for yield gap closure and desalinations ability to provide water could be key (Antia, 2022; Davis et al., 2017).

We use Rosa et al.'s (2018) calculations on the biophysical irrigation requirements for closing the yield gap of 16 major crop types. We consider barley, cassava, groundnuts, maize, millet, oil palm, potatoes, rapeseed, rice, rye, sorghum, soybeans, sugar beet, sugar cane, sunflower, and wheat. These crops account for 73% of the planet's cultivated areas and 70% of global crop production (Rosa et al., 2018). Yield gap closure requires a further 788 cubic kilometres of water annually (see figure 1). This also includes substituting for unsustainable irrigation when blue water consumption equals or exceeds the renewable blue water availability comprising over 39% of current irrigation volumes. In their follow up study Rosa et al. go into further detail on the limits of sustainable expansion under a 3 degree warmer climate using the same modelling assumptions (Rosa et al., 2020). Rosa et al. conduct their analysis at a 5-arcminute scale with a base year 2000, but their data is only available as country total volumes, we aggregate these country volumes into the regions of our analysis.

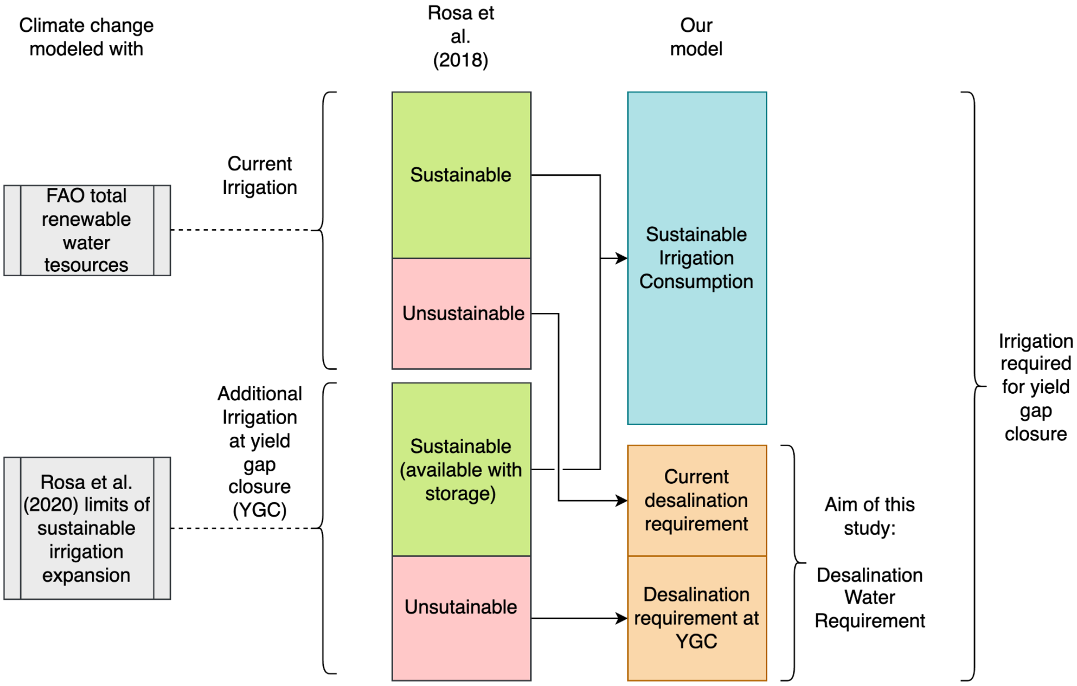

Figure 1: Our approach visualised: sustainable blue water consumption and desalination water requirement (unsustainable blue water consumption) and the underlying data used to achieve yield gap closure illustrated, derived from Rosa et al. (2018). climate change accounted for with data from the food and agricultural organisation (2018) and Rosa et al. (2020) (own creation).

We approximate the effects of climate change in two ways (illustrated in figure 1). First we model a potential decrease in the amount of sustainable water available for current irrigation practices. We use projections for total renewable water resources in 2070/2090 for RCP 2.6 and RCP 8.5 obtained from the Food and Agriculture Organization's projection for total renewable water resources (based on six hydrological models for the ISI-MIP project) (FAO, 2018). Total renewable water resources are consumed by agriculture, municipal uses, and industry (FAO, 2022). We assume that the share of agricultural withdrawals remains constant as the total renewable water resources are affected by climate. We interpolate total renewable water resources linearly between 2000 and 2080. We can then calculate in 2050 and for RCP2.6 and RCP8.5 (eq. 1).

$$S_{RCP} = S_{2000} + \left(\frac{S_{2080_{RCP}} - S_{2000}}{2080 - 2000} \right) \times 50 \tag{1}$$

Where S_{RCP} is the sustainable water used for current irrigation practices in 2050 under a specific RCP scenario. S_{2000} is the sustainable water available for current irrigation practices in the year

2000. $S_{2080_{RCP}}$ is the sustainable water available for current irrigation practices in the year 2080 under the specific RCP scenario. RCP represents the specific Representative Concentration Pathway (either RCP 2.6 or RCP 8.5).

Second we model the effects of climate change on the amount of sustainable water resources available for irrigation with storage. Rosa et al. (2020) provide estimations on this for a 3 °C warmer climate. We extrapolate these data to estimate the amount of water available with storage in 2050 using global temperature estimation for the scenarios from the Intergovernmental Panel on Climate Change sixth assessment report 1.7 °C for RCP2.6 and 2.4 °C for RCP8.5 (Masson-Delmotte et al., 2021)(eq. 2). We assume that countries will build storage to meet their own requirements, but not those of other countries. One country's surplus storage capacity can not compensate for another's deficit.

$$Storage_{RCP} = Storage_{3C} \times \left(\frac{T_{RCP}}{3}\right) \tag{2}$$

Where $Storage_{RCP}$ is the sustainable water resources available for irrigation with storage in 2050 under a specific RCP scenario. $Storage_{3C}$ is the sustainable water resources available for irrigation with storage available in a 3 °C warmer climate. T_{RCP} is the projected global temperature increase in 2050 under a specific RCP scenario.

We make two key assumptions: First, that crop biophysical requirements are constant: the volume of required irrigation for yield gap closure remains constant over time and climate. Second, we assume that desalinated water can be provided where it is necessary. However, we envision regional hubs located near demand centres and electrical grid infrastructure, as the infrastructure does not need to be centralised. The desalination irrigation volume for current practices (eq. 3) and the desalination irrigation at yield gap closure is then (eq. 4)

$$Desal = (S - Storage * E)/E \tag{3}$$

$$Desal_{YG} = (\text{biophysical requirement at YG} - (S - Storage * E))/E \tag{4}$$

Where $Desal$ is the volume of desalination required to eliminate unsustainable practices. $Desal_{YG}$ is the desalination irrigation volume for yield gap closure. Irrigation requirement at YG is the volume of irrigation water required to close yield gaps estimated by rosa et al. (2018). S is the sustainable water available for current irrigation practices. $Storage$ is the volume of sustainable water available for irrigation with storage. Accounting for the difference between the biophysical requirement and the actual requirement is done by incorporating the irrigation water application efficiency E. E is multiplied with $Storage$ to account for application losses when using storage fed water for irrigation.

We analyse two extents to which desalination can be deployed firstly for eliminating unsustainable withdrawals and secondly for closing yield gaps. For these two extents we calculate an optimistic scenario requirement and pessimistic scenario requirement. The optimistic scenario makes three key assumptions. First: RCP2.6 is followed. Second: we use the highest possible irrigation efficiency scenario of Caldera & Breyer (2020) where application efficiency E reaches 90% in 2050. Third: all water usable with future storage is used. The pessimistic scenario makes three key assumptions: First: RCP8.5 is followed. Second: irrigation application efficiency E sees no further increase from current levels (see table S1). Third: additional water is not available from storage because no additional storage is constructed. This approach allows us to estimate a lower and upper boundary for desalination requirements in agriculture.

To understand the scale and cost associated with the projected volume of global desalination and put it into perspective we assess the amount of people potentially fed by desalinated irrigation in 2050 when eliminating unsustainable irrigation withdrawals and at yield gap closure. For this we assume 3343 kcal/p/d, accounting for food losses and waste (as used by others (Davis et al., 2016; Rosa et al., 2020; Schmitt et al., 2022). The calories per irrigation volume is derived from our data (see table S4). A limitation of this approach is that it does not take into account changes in global calorie consumption and measures taken to reduce food waste by 2050, potentially altering the amount of people fed from desalinated irrigation.. We use data from Caldera & Breyer, which provides projections on the average levelized cost of water (LCOW) for 2050 for different regions (see table S2). LCOW is a standard approach for assessment and comparison of desalination technologies (Atia et al., 2021; Caldera et al., 2016; Papapetrou et al., 2017). We assume that in 2050 all desalination is powered from renewable energy. Renewable energy powered seawater reverse osmosis (SWRO) has shown reductions in LCOW and emissions compared to fossil powered SWRO, therefore full adoption is assumed (Caldera & Breyer, 2018; Elsaid et al., 2020; Papapetrou et al., 2017). Energy consumption for SWRO is assumed at 2.6 kWh/m^3 in 2050 per Caldera & Breyer (2019). We calculate brine production using the recovery rate (0.42) from Jones et al. (2019). The recovery rate of the desalination process describes the ratio of fresh water to brine produced. An example: at our recovery rate (0.42) 42% of the intake seawater is converted to potable freshwater and 58% is brine. We multiply all assumed amounts with the volume of desalinated water for 2050 and convert units where necessary (eq. 5-7). A limitation of this approach is that pathways of technological improvements and change are not considered, many third generation technologies that can reduce cost and emissions are being researched and will likely see some form of deployment in 2050 (El Haj Assad et al., 2022; Park & Lee, 2022; Zapata-Sierra et al., 2021). Considering these technologies are outside the scope of our research, the result of this will be higher estimates on cost, energy consumption and brine production.

$$\text{Cost} = \text{LCOW} \times \text{Desalination requirement} \tag{5}$$

$$\text{Energy requirement} = \text{Energy consumption} \times \text{Desalination requirement} \quad (6)$$

$$\text{Total Brine Produced} = \left(\frac{1 - \text{Recovery Rate}}{\text{Recovery Rate}}\right) \times \text{Desalination requirement} \quad (7)$$

Results

We estimate global demand for agricultural irrigation to eliminate unsustainable blue water withdrawals for major crop production at 220-651 km^3 y^{-1} (table 1, figure 2). This is in line with Caldera & Breyer's (2019) lower limit estimation (228.3 km^3 y^{-1}). We estimate the total desalination volumes useful in agriculture when closing yield gaps between 848-2175 km^3 y^{-1} in agreement with Caldera & Breyer's upper limit (2019) (1132 km^3 y^{-1}). The difference in volume required between RCP2.6 and 8.5 at a global level appears to be low at between 10-15 km^3 y^{-1} (see table S3). This can be deceptive as a large consequence of global warming is the increase in the requirement for more water storage, not the absolute volume available (Rosa et al., 2020).

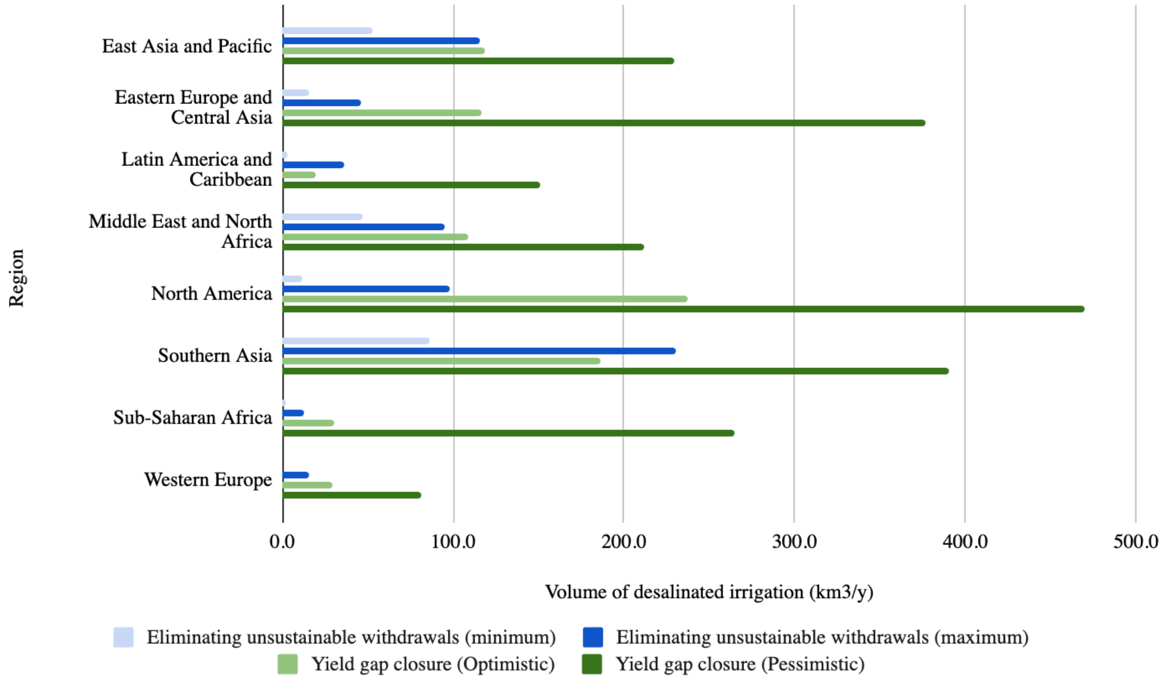

Figure 2: Volume of desalinated irrigation in cubic kilometres per year required to eliminate unsustainable blue water withdrawals in irrigated agriculture and to close the yield gap. Minimum:RCP2.6 with storage, Maximum RCP8.5 without storage.

When the aim is to eliminate unsustainable blue water withdrawals in current irrigation practices there are high requirement in East Asia and Pacific (EAP)(53-116 km^3 y^{-1}), the Middle East and North Africa (MENA)(47-96 km^3 y^{-1}) and Southern Asia (SA)(86-230 km^3 y^{-1}). North America (NA)(12-98 km^3 y^{-1}) has high demand that can be mitigated largely with storage (Schmitt et al., 2022). These regions contain some of the world's major agricultural baskets such as the North China Plains and the Murray-Darling Basin of Australia (EAP), the US High Plains and California's Central Valley (NA), and the Indo-Gangetic Basin (SA). where irrigation practices are regularly unsustainably depleting groundwater resources (Gleeson et al., 2012; Jain et al., 2021; Rodell et al., 2018; Scanlon et al., 2023). The MENA region, largely dependent on rainfed agriculture, has high desalination demand due to increased water stress from a combination of extreme heat, drought, and aridity conditions exacerbated by climate change. (Drine, 2011; Waha et al., 2017). Lower requirements are expected in Eastern Europe and Central Asia (EECA)(16-46 km^3 y^{-1}), Latin America and Caribbean (LAC)(3-36 km^3 y^{-1}), Sub Saharan Africa (SSA)(2-12 km^3 y^{-1}), and Western Europe (WE)(0-15 km^3 y^{-1}). These regions are still largely dependent on rain-fed agriculture having either smaller shares of irrigation due to high rainfall (WE) or economic constraints (EECA, LAC, SSA)(de Fraiture & Wichelns, 2010; Droppers et al., 2021; Rosa, Chiarelli, Rulli, et al., 2020). SSA, while highly impacted by climate change, has low demand largely due to an underinvested agricultural system with low irrigation share and an over reliance on rain (Biazin et al., 2012). We observe that in the EAP,MENA, and SA optimistic yield gap closure volumes are only slightly higher than or even lower than pessimistic elimination requirements (table 1, figure 2).

Table 1

The desalination demand in cubic kilometres per year (km3/y) for each of the regions for 2050 . demand given for eliminating unsustainable blue water withdrawals of currently irrigated agriculture and at yield gap closure.

Region	Demand			
	Eliminating unsustainable withdrawals		Yield gap closure	
	Minimum	Maximum	Minimum	Maximum
East Asia and Pacific	53.2	116.0	118.3	229.7
Eastern Europe and Central Asia	15.6	46.4	116.9	376.7
Latin America and Caribbean	3.1	36.4	19.3	151.4
Middle East and North Africa	47.4	95.5	109.1	211.9
North America	12.0	98.2	237.7	469.8
Southern Asia	86.4	230.3	186.3	390.0
Sub-Saharan Africa	1.9	12.4	30.3	265.0
Western Europe	0.0	15.3	29.7	80.9
Global	219.7	650.6	847.7	2175.4

Potential extent of desalinated irrigation at yield gap closure

All regions see significant increases in desalination requirements when closing yield gaps (table 1, figure 2). We observe that when closing yield gaps it is paramount that there is a very large difference in the amount of water required between the optimistic and pessimistic scenarios. Most regions require about double or triple the amount of desalination in the pessimistic scenario. For

SSA We observe the highest difference at nearly an order of magnitude between scenarios, this region is heavily impacted by climate change and has the lowest current irrigation water application efficiency at 34% (see table S1). The regions with a high desalination requirement to eliminate unsustainable withdrawals: EAP, MENA, and SA see an increase in requirements (~100%) that are orders of magnitude lower than regions that have lower desalination requirements EECA, LAC, SSA (~400-2000%). This can be explained in conjunction with our earlier observations. The high desalination requirement regions have generally more intensive farming and higher yields due to their existing (extensive) use of irrigation (Beltran-Pena et al., 2020; Elliott et al., 2014; Scanlon et al., 2023). While low elimination requirement regions increase their yields greatly by the use of irrigation on rainfed lands with green water stress (Biazin et al., 2012; de Fraiture & Wichelns, 2010; Droppers et al., 2021; Jalava et al., 2016). Sub Saharan Africa and Latin America and Caribbean show a large increase between storage and non-storage scenarios (about 3x and 4x respectively). In these regions blue water resources would be available but go unused due to a combination of geography, temporal availability and or poor management; storage would allow for their use (Boelens et al., 2011; Hassan & Tularam, 2018; Onyutha, 2021; Salazar et al., 2022; Schmitt et al., 2022). The feasibility of the construction of storage in these, often economically disadvantaged and or politically unstable regions, is debated (Biazin et al., 2012; Boelens et al., 2011; Hillocks, 2014; Schmitt et al., 2022). North America and Western Europe present a separate trend with low elimination requirements and percentage-wise high increases at yield gap closure. Western Europe has a developed agricultural system with high yields that is largely unconstrained by blue and green water availability (Rosa et al., 2020; Schils et al., 2018). At 26-55 km^3 y^{-1} its desalination requirements are among the lowest regional amounts. North America has an intensive agricultural system which is largely rainfed in combination with irrigation with a dependence on unsustainable groundwater consumption and high susceptibility to droughts (Gumidyala et al., 2020; Lopez et al., 2022; Lu et al., 2020).

Desalinated irrigation's contribution to global food security

We estimate that globally 550 million to 1 billion people can be fed from desalinated irrigation when it is used to eliminate unsustainable blue water withdrawals (table 2 above). To our knowledge this estimate is novel, though the difference of 450 million people that would be fed from storage if it was constructed aligns with Schmitt et al. (2022) lower estimate (631±145 million people). All regions show that there is potential for desalinated agriculture to feed millions to hundreds of millions of people when used to eliminate unsustainable irrigation water withdrawals with desalinated water. When considering the application of desalinated irrigation to meet yield gap water requirements the amount of people rises to the billions of people globally (3.5-5 billion additional people). In 2050, the world's urban landscape will be significantly transformed, with substantial population growth concentrated in specific regions. South America (LAC), Africa (MENA,SSA), and Asia (EAP,SA) are expected to grow in population at a disproportionate rate compared to the rest of the world from now to 2050 (He et al., 2021; H. Liu et al., 2018; Walker, 2016). These regions show significant potential to feed people with desalinated irrigation at yield gap closure at 134-489 million, 434-854 million and 2.7-3.5 billion people respectively. We observe a large variation in the regional amount of people fed per km3 of desalinated water, likely due to other reasons that yield gaps are not being combined with the share of rainfed agriculture in the region (Gerber et al., 2024; Lobell et al., 2009; Mueller et al., 2012). We find that desalinated water would globally and regionally be best suited to fulfil yield gap requirements rather than the elimination of unsustainable blue water withdrawals from an isolated people fed per unit of desalination perspective.

Table 2

The amount of people potentially fed from desalinated irrigation in millions of people per year. Eliminating unsustainable withdrawals describes current irrigation extents. Yield gap closure describes the amount of people fed when irrigation is expanded and intensified to meet volumetric yield gap requirements.

Global Region	Eliminating unsustainable withdrawals			Yield gap closure		
	Optimistic	Pessimistic	million people fed per km3	Optimistic	Pessimistic	million people fed per km3
	Million people			Million people		
East Asia and Pacific	372	522	7.8	1595	1995	15.0
Eastern Europe and Central Asia	9	14	0.7	619	998	5.9
Latin America and Caribbean	6	35	2.3	134	489	7.7
Middle East and North Africa	34	44	0.8	280	350	2.9
North America	20	103	1.9	366	451	1.7
Southern Asia	148	253	1.9	1147	1547	6.8
Sub-Saharan Africa	1	4	0.8	154	508	5.6
Western Europe	0	33	3.2	121	249	4.5
Global	550	1007	2.8	4109	6052	5.4

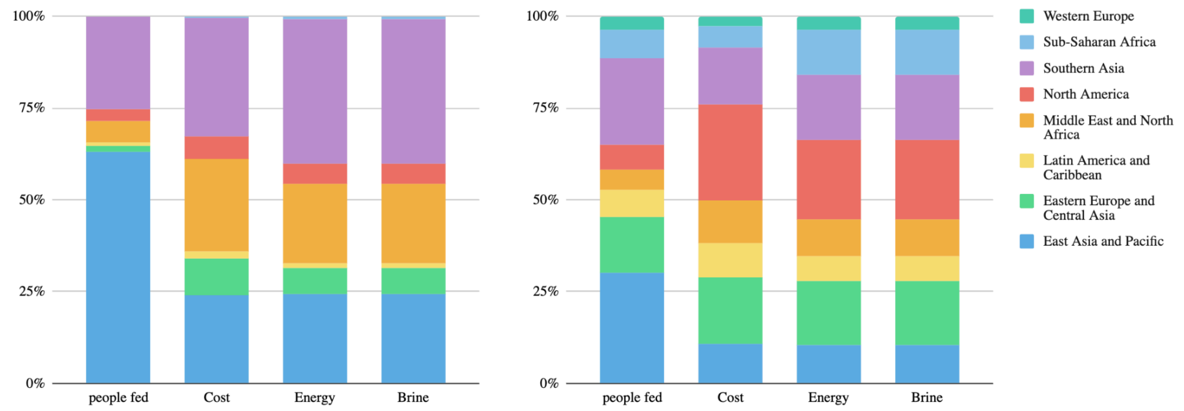

Figure 3: percentage share of total amounts of people fed, water costs, energy requirement, and brine production at (Left) at optimistic elimination requirements, (right) pessimistic yield gap closure requirements.

Operational impact and requirements of desalinated irrigation

We calculate that the volume of desalination irrigation water will cost between 160-2000 billion euros annually globally in 2050 (table 3 below). Our estimate is in line with annualised costs (543 b€) estimated by Caldera & Breyer (2020) for 2050. The mean value of irrigation water is currently estimated at 0.13$/m^3 with price increasing to 2.50-6$/m^3 under extreme water scarcity (D'Odorico et al., 2020). Comparatively the levelised cost of water for desalination in 2050 averages from 0.4-1.8€/m^3. Global energy requirements are estimated at 571-5656 tWh. Comparatively the International Energy Association estimates that renewables generated 8500 tWh in 2022 (International Energy Agency, 2024). energy requirements when eliminating current unsustainable practices under optimistic conditions (571 tWh) are similar estimates for the current irrigation in agriculture at 526 tWh (1896 pJ)(Qin et al., 2024). The pessimistic scenario sees a near tripling of these requirements (1691 tWh). Closing yield gaps will require large amounts of renewable energy This desalination would produce between 303 and 3000 km^3 of brine yearly, 6 to 60 times more than the current annual brine production (52 km^3 y^{-1}) estimated by Jones et al. (2019).

In line with our earlier findings the EAP, MENA, SEA and NA regions account for a majority of the cost, energy requirement and Brine production as these regions have extremely large agricultural areas and large populations (Gleeson et al., 2012; Jain et al., 2021; Rodell et al., 2018; Scanlon et al., 2023). The MENA region is particularly arid and water stressed (Drine, 2011; Waha et al., 2017). At yield gap closure (t3. figure 3 above) EAP appears the most potent region for desalinated irrigation with a large share of a people fed globally (>25%) for a proportionally smaller amount of impacts compared to other regions. SSA is a region with a high potential to feed people (504 million) for a proportionally low cost (102 b€) this is mostly due to a low average regional LCOW, high dependence on rainfed agriculture and low current yields (Biazin et al., 2012; Caldera & Breyer, 2020; Hillocks, 2014) (table S2,S4). Desalination could play a vital role as storage deficits are predicted even when all potential dam based storage is constructed (Schmitt et al., 2022). When eliminating unsustainable blue water withdrawals we observe that the EAP region in particular is well suited to desalinated irrigation with a high share of the total people fed for disproportionately small impacts (figure 3) because of a combination of low LCOW and high potential for the expansion of irrigation (Beltran-Pena et al., 2020; Schmitt et al., 2022).

Table 3

Operational impacts for the volume of desalination required to eliminate unsustainable blue water withdrawals in currently irrigated agriculture and to close yield gaps. Cost in billion euro, energy requirement in terawatt hour)(energy consumption: 2.6kWh/m3) , and brine production (recovery rate: 0.42) in cubic kilometres.

Eliminating current unsustainable withdrawals

Global Region	Cost billion €		Energy (TWh)		Brine km3	
	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic
East Asia and Pacific	26.6 - 63.9	58 - 139.2	138.4	301.7	73.5	160.2
Eastern Europe and Central Asia	9.3 - 28	27.9 - 83.6	40.4	120.8	21.5	64.1
Latin America and Caribbean	3.4	40.1	8.1	94.7	4.3	50.3
Middle East and North Africa	47.4	95.5	123.4	248.3	65.5	131.9
North America	12.0	98.2	31.2	255.4	16.6	135.6
Southern Asia	60.5	161.2	224.8	598.9	119.4	318.1
Sub-Saharan Africa	0.8	4.9	4.9	32.1	2.6	17.1
Western Europe	0.0	9.2	0.0	39.8	0.0	21.1
Global	160 - 216	495.1 - 632	571.1	1691.6	303.3	898.5

Yield gap closure

Global Region	Cost (billion €)		Energy (TWh)		Brine (km3)	
	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic
East Asia and Pacific	59.2 - 142	114.8 - 275.6	307.7	597.1	163.4	317.1
Eastern Europe and Central Asia	58.4 - 140.3	188.3 - 452	303.9	979.3	161.4	520.2
Latin America and Caribbean	21.3	166.6	50.3	393.7	26.7	209.1
Middle East and North Africa	109.1	211.9	283.7	550.9	150.7	292.6
North America	237.7	469.8	617.9	1221.5	328.2	648.8
Southern Asia	130.4	273.0	484.5	1014.0	257.3	538.6
Sub-Saharan Africa	12.1	106.0	78.9	689.0	41.9	366.0
Western Europe	17.8	48.5	77.1	210.3	41.0	111.7
Global	646 - 810.7	1578.9 - 2003.4	2203.9	5655.9	1170.6	3004.1

Note. Ranges are given for cost when regional averages are comprised from multiple sub regions

Discussion

We quantify the potential for desalinated irrigation in agriculture to supplement current strained blue water supplies and meet future irrigation needs. We model a lower and upper boundary for desalination's use in agriculture for eight global regions, using data on yield gap closure requirements and on the limits of sustainable irrigation expansion. We then estimate the associated annual cost of water, energy consumption, and brine emissions. We find that desalination can significantly contribute to future food production strained by growing food demand, increasing water scarcity, and a changing climate. Desalination can provide water in current and future water insecure areas vital to maintain and increase yields. Our research shows that desalination has the potential to both eliminate current and future unsustainable blue water withdrawals and meet yield gap volume requirements (Rosa et al., 2020; Schmitt et al., 2022).

Our results contribute to the academic effort to examine the use of desalination in agriculture by estimating previously largely unquantified desalinated irrigation requirements at a global level with regional distinction. It also furthers the research on how to sustainably close yield gaps by offering a fresh perspective grounded in water production through desalination. Our findings, while obtained following a novel method, align with Caldera & Breyer's previous estimates on desalination requirements (Caldera & Breyer, 2019, 2020). Results indicate that desalinated water could sustainably feed an additional 500 million to 1 billion people when replacing unsustainable blue water withdrawals within the current system. An additional 3 to 4 billion people could be sustainably fed when providing water resources to close yield gaps. Our optimistic estimates the annual costs of desalinated water to be around 160 to 800 billion euro annually rising to 500-2000 when pessimistic. The costs encapsulate both the opex and capex of renewable powered desalination and the required transportation infrastructure. These costs are prohibitively high: the food and agribusiness sector is estimated to be worth around 5 trillion dollars (Goedde et al., 2015). While the sector is expected to increase in value from now to 2050 water costs that would require between 3-40% of current total market value would be prohibitively expensive. Research into the future value of water suggests that the value (and costs) of blue water will rise as water stress increases, while costs of desalinated water are not linked to water stress (Chebly, 2014; D'Odorico et al., 2020). This will increase the viability of desalinated agriculture in areas with water stress, which there will be more of in 2050, but it is unlikely that desalinated irrigation is a solution that will see deployment at the scale we illustrate it could be used from a cost perspective. The annual cost of water in our research for 2050 includes the opex and capex of desalination, transportation, and associated renewable capacity. However, this figure doesn't reflect the total year-over-year investment needed to reach the required capacity by 2050, which would be significantly higher as capacity building requires year over year investments. According to Caldera & Breyer (2020), the global average LCOW is expected to decrease from 2.44€/m^3 at baseline to 1.07€/m^3 by 2050.

We estimate annual energy requirements of desalination necessary to eliminate unsustainable withdrawals in 2050 at 570 to 1700 tWh. Qin et al. (2024) estimate annual energy consumption used by the current irrigation system 500 tWh. 90% of this amount comes from groundwater pumping, a practice that at first glance would be largely eliminated by substituting it with desalinated irrigation water. Current energy requirements are associated with 15% of agricultural GHG emissions (Lopez et al., 2022; Qin et al., 2024). Although desalination can be powered by sustainable energy, the amount needed (~570-5650 tWh annually) seems unrealistically high in light of current renewable energy production capacity available (8500 tWh in 2022). Though this capacity is slated to triple by 2030 following COP28's pledge (UNFCCC, 2023) and can be expected to be even larger in 2050. Energy requirements seem to be a prohibitive barrier for desalinated irrigation as a widely employed regional solution. That these requirements be met in certain cases where desalination is the most logical option is not unthinkable. When we look at these demands at a country level, we observe a development trap for desalination: developing nations, for instance South Africa, characterised by inadequate infrastructure, face a paradoxical situation where low irrigation application efficiency necessitates more desalination and thus better infrastructure.

In 2050 we estimate brine volumes are predicted to be 6 to 60 times the current estimates by Jones et al (2019) (~50 km^3 y^{-1}), at 300 to 3000 km^3 per year. Estimates brine disposal at a much larger scale than currently is a manageable issue (Pistocchi et al., 2020). Still, the improper disposal of brine can be catastrophic: contaminates freshwater bodies, causing significant harm to broader ecosystems. Studies highlight that high salinity from brine can disrupt marine life, contaminate surface and groundwater, degrade soil quality, and reduce yields (Ahmad & Baddour, 2014; Elsaid et al., 2020; Panagopoulos et al., 2019; Zörb et al., 2019). Brine management research is ongoing: with technological advancements in membrane and reverse osmosis showing promising results in reducing volumes and extracting valuable resources such as lithium (Ghernaout, 2019; Lundaev et al., 2022; Sun et al., 2021; Zhang et al., 2019). This paradigm shift in recognizing brine as a valuable resource rather than a waste byproduct redefines its role, increasing its economical value. (C. Liu et al., 2023; Mavukkandy et al., 2019; Pistocchi et al., 2020).

In a broader context feeding the global population is an existentially fundamental and ever-increasing challenge. Previous research has shown that, while possible, concrete action is necessary to rise to this challenge. This requires substantial changes in current food production practices (Beltran-Pena et al., 2020; Gerten et al., 2020). Closing yield gaps across different regions and crop types would go a long way towards solving this challenge (Foley et al., 2011; Lobell et al., 2009; Mueller et al., 2012). Unsustainable blue water withdrawals for irrigation, inadequate blue water availability, and green water scarcity on rainfed lands, in part, work against yield gap closure. (Davis et al., 2017; Pradhan et al., 2015). Recent studies have also found that global irrigation withdrawal projections are deceptively low, thus suggesting a much bigger future requirement than previously understood (Puy et al., 2020, 2022). This, combined with recent findings that the expansion potential of sustainable irrigation is constrained even when all potential future dams are constructed, underpins the much needed search for alternative solutions (Rosa et al., 2020; Schmitt et al., 2022). Our research into desalinated irrigation in agriculture aims to make a high level contribution to this search.

However, looking at agriculture and irrigation through a systems lens, desalination and extra storage as solutions are addressing the symptoms of underlying problems. Firstly, we are wasting too much water. While it's possible to create more water to meet our demands; from a systems perspective the underlying issue should be addressed. Nearly half of water being used for irrigation is wasted, globally the average application efficiency is only 55% (Hoogeveen et al., 2015),. Widespread adoption of more efficient technologies such as sprinkler irrigation and drip irrigation would greatly reduce water wastes in irrigated agriculture (Fyles & Madramootoo, 2016; van der Kooij et al., 2013). It is when we have reached the limits of application efficiency that it would make sense to start using desalinated water in this regard. Secondly, our animal-based diets are wasting water. Calories from animal sources require significantly more water than plant sources (Davis & D'Odorico, 2015; Pradhan et al., 2013). Switching to more plant-based diets can reduce the global water footprint (Jalava et al., 2016; Kim et al., 2020). Using estimates by Pradhan et al. (2013) that 40% of global crop calories are used as livestock feed and that about 4 kcal of crop products generate 1 kcal of animal product. In a hypothetical situation, where we halve animal protein consumption in 2050: crop requirements are reduced by about 30%. Green and blue water consumption is reduced by 21% and 14% respectively when removing animal protein from diets (Jalava et al., 2016). Changing diets would lead to substantial water savings globally, especially in regions heavily reliant on animal products. In Europe, a shift to vegetarian diets could cut the water footprint by 27-41% (Vanham et al., 2013). These reductions in water consumption could have significant, yet currently unquantified, influence on desalination requirements.

Our estimations for desalination account for irrigation application efficiency but they do not take into account dietary shifts. Our study is limited by our modelling approach, stemming from a simplification of more complex interactions as they appear in reality. Our scope is a quantification of desalination for irrigation employed at a global level. Modelling these complex interactions is outside of our scope. This results in 4 key limitations. Firstly, site and technology specific variables such as: crop type, water salinity, temperature, pumping distance, potential storage, energy mix, desalination efficiency, and potable water conversion rate all have a significant impact on desalinated water requirement, cost, brine emissions, and energy consumption (Caldera & Breyer, 2019; El Haj Assad et al., 2022; Elsaid et al., 2020). We do not account for this variability and use regional and global averages. In reality these factors impact the viability of desalination in any area, but this variance is not visible in our results. For our optimistic scenario we assume that 90% irrigation application efficiency is achieved by 2050. This assumption is also used by one of Caldera

& Breyers (2020) scenarios and research suggests this application efficiency is possible (Fyles & Madramootoo, 2016). However, this optimistic scenario is the best hypothetical case. Regions with strong economies and high current efficiencies such as North America an Western Europe may reach these efficiencies; but it is unlikely that all regions, particularly ones with weak economies and underdeveloped infrastructure such as Sub Saharan Africa do. For our Pessimistic scenario we assume that application efficiency would not see further increase from current percentages (see table S1). This assumption would most likely be overly pessimistic as high costs associated with desalinated irrigation water would incentivise extra care in applying it efficiently to minimise the required capacity and thus costs of the operation. What is clear in any case from our modelling is that there are substantial gains to be made by improving application efficiency to reduce water waste before desalination is introduced.

Thirdly, we do not account for the projected disproportionate growth of human or industry water consumption (Bijl et al., 2016). In line with our findings, observations show that increasing population and economic growth are more relevant in creating extreme water stress in developing countries than climate-induced variations (Elliott et al., 2014; J. Liu et al., 2017; Wada et al., 2013, 2016). Studies show that especially in urban areas renewable water resource use is rapidly increasing (Flörke et al., 2018; He et al., 2021). As total water consumption grows for other uses, its availability does not. Logically, more water needs to be created through desalination to meet the future needs than currently estimated. Finally, our research has primarily focused on examining the desalination demands of agriculture in isolation from the socio-economical and natural systems that it is part of. Hence this simplification does not capture the complexity of the seasonal and transboundary nature of water and agricultural systems (D'Odorico et al., 2018; FAO, 2018, 2022; Joseph et al., 2020). To give an example, catastrophic climate events for global agriculture production such as the Atlantic Meridional Overturning Circulation (AMOC) collapsing are not accounted for. The weakening or collapse of the AMOC has far-reaching consequences for global agriculture, affecting precipitation patterns, temperature, and biogeochemical cycles (Armstrong et al., 2019; Ciemer et al., 2021; Jackson et al., 2015; P. D. L. Ritchie et al., 2020). These changes necessitate adaptive strategies and technological innovations to mitigate the potential impacts on agricultural productivity and food security. It stands to reason that these events would escalate the demand for a reliable water source such as desalination.

From these limitations we envision opportunities for future research. Firstly, at the local scale: research into desalination at smaller scales and its interplay with community renewable energy systems (RES) could help develop frameworks and methodologies to estimate desalinated irrigation potential at a site specific level with more accuracy. Local accuracy could then serve as the basis for a bottom up estimation of global requirement. The focus on local level also reveals a key strength of desalination that remains hidden in the global approach: its highly scalable nature. Constructing a small desalination plant can be tailored to meet the needs of a small agricultural community, where constructing a water reservoir is often a much larger scale and complex endeavour. To get started on the path of widespread adoption of desalination practices, it would be interesting to develop a methodology that will allow us to identify locations where such small scale operations are most feasible.

Secondly, at a larger regional scale: modelling should include the transboundary nature of our water system from a regional water resources availability, economical, and political cooperation perspective. It is important that desalination irrigation be modelled at a watershed level to better understand how desalinated irrigation in one area may free up blue water resources in another where desalination is less ideal. Further modelling is also necessary to include the effects of population growth and associated water consumption as well as industrial water consumption, as their demands increase disproportionately alongside agricultural needs (FAO, 2022). Finally, To address the problem of water security in agriculture systematically: comparative research is needed between demand side solutions: improved irrigation application efficiency, reducing dietary water demands and supply side solutions: desalination and constructing additional storage. Such research should focus on the environmental, social and economic cost of all solutions to gain a true understanding of how to meet future water demands sustainably. Further, research should be conducted in how desalination in agriculture can help mitigate the system-threatening effects of catastrophic climate change such as AMOC collapse.

In conclusion, irrigation from desalination could play a limited role in the ability to grow more food unconstrained by the limits and availability of sustainable blue water resources, but more research is needed to gain a complete understanding of its future prospects. Producing desalinated water for irrigation uses is currently often deemed unnecessary or too expensive to be considered outside of a handful of specific use cases and these barriers persist into the future. However, as food demand growth, climate change, and economic growth put pressure on our agricultural system to produce higher yields with fewer and less secure water resources, desalination may become a viable source of future water security. The economic or energy factors seem to be prohibitive barriers towards widespread use given the context of the entire agricultural system costs and future renewable energy capacity expansion. The increased amount of brine associated with required desalination production does not seem to be an unmanageable issue. Furthermore with a more circular approach, brine could potentially be converted into a valuable resource instead of being treated as a waste product. Of the eight regions researched, East Asia and Pacific and Sub-Saharan Africa regions show a high potential. However, all eight regions need to produce more food in the future and water availability is a global issue. We have outlined several promising pathways for future research that can be conducted to gain a better understanding of desalinated irrigation's potential and role in a future agricultural system. Our global and regional estimation serves as a starting point for further research to deepen the understanding of desalinated irrigation's potential and models with more complexity. In sum, where desalinated irrigation can produce the water to feed future generations, cost and energy requirements are prohibitive barriers towards large scale deployment.

Supplementary materials

Table S1

irrigation water application efficiency as used in the model. For the pessimistic scenario data was aggregated from smaller subregions.

Region	GlobWAT Subregions	Average Irrigation Efficiency %	
		Optimistic	Pessimistic
East Asia and Pacific	East Asia, Mainland Southeast Asia, Maritime Southeast Asia, Australia and New Zealand	90%	58%
Eastern Europe and Central Asia	Russian Federation, Eastern Europe, Central Asia, Caucasus	90%	45%
Latin America and Caribbean	Mexico, Central America, Greater Antilles, Lesser Antilles, Guyanas, Andes, Brazil, South America	90%	42%
Middle East and North Africa	Northern Africa, Arabian Peninsula, Iran, Near East	90%	58%
North America	North America	90%	56%
Southern Asia	South Asia	90%	58%
Sub-Saharan Africa	Sudano–Sahel, Gulf of Guinea, Central Africa, Eastern Africa, Southern Africa, Indian Ocean islands	90%	34%
Western Europe	Northern Europe, Western Europe, Central Europe, Mediterranean Europe	90%	68%
Global		90%	55%

Note: Derived from Hogeveen et al (2015) and Caldera & Breyer (2020)

Table S2

The regional average levelized cost of water (LCOW) in euro per cubic metre for renewable energy powered seawater reverse osmosis used in our research.

Global Region	LCOW
	€/m3
East Asia and Pacific	0.5 - 1.2
Eastern Europe and Central Asia	0.6 - 1.8
Latin America and Caribbean	1.1
Middle East and North Africa	1.0
North America	1.0
Southern Asia	0.7
Sub-Saharan Africa	0.4
Western Europe	0.6

note. Source: Caldera & Breyer (2020). LCOW given as a range when region is comprised of multiple regions in source data

Table S3

The biophysical desalination demand in cubic kilometres per year (km3/y) for each of the regions for 2050 RCP2.6 and RCP8.5 simulation. Current irrigation practices describe when desalination is used to eliminate unsustainable withdrawals of currently irrigated agriculture. Yield gap closure describes volumes of water required to close yield gaps. with and without storage describes the use of blue water resources only available with storage.

Region	RCP	Demand			
		Eliminating current unsustainable withdrawals		Yield gap closure	
		with storage	without storage	with storage	without storage
East Asia and Pacific	2.6	53.2	66.6	118.3	132.2
	8.5	47.8	116.0	106.8	229.7
Eastern Europe and Central Asia	2.6	15.6	20.4	116.9	169.1
	8.5	14.4	46.4	108.2	376.7
Latin America and Caribbean	2.6	3.1	12.8	19.3	61.4
	8.5	4.1	36.4	19.1	151.4
Middle East and North Africa	2.6	47.4	51.3	109.1	118.5
	8.5	44	95.5	101.2	211.9
North America	2.6	12.0	54.8	237.7	262.9
	8.5	14.3	98.2	216	469.8
Southern Asia	2.6	86.4	132.2	186.3	224.7
	8.5	79.4	230.3	170.3	390.0
Sub-Saharan Africa	2.6	1.9	3.7	30.3	89.7
	8.5	0.9	12.4	25.2	265.0
Western Europe	2.6	0.0	5.7	29.7	50.4
	8.5	2.8	15.3	32.2	80.9
Global	2.6	219.7	347.5	847.7	1108.9
	8.5	207.7	650.6	779	2175.4

Table S4

Volume of blue water, sustainable and unsustainable combined, used in current irrigated agriculture and required at yield gap closure in cubic kilometres per year and associated calories in 10^15 Kcal per year of the 16 crop types in our research. Current irrigation describes agriculture where irrigation is currently deployed both sustainably and unsustainably, yield gap closure describes the volume of irrigation required and associated calories produced at yield gap closure

Global Region	Current irrigation		Additional to yield gap closure		Total at yield gap closure	
	Water (km3/y)	Calories (10^15 Kcal)	Water (km3/y)	Calories (10^15 Kcal)	Water (km3/y)	Calories (10^15 Kcal)
East Asia and Pacific	155.3	1.47	65.7	1.20	221.0	2.67
Eastern Europe and Central Asia	56.2	0.05	148.4	1.07	204.6	1.11
Latin America and Caribbean	38.9	0.11	48.5	0.46	87.4	0.56
Middle East and North Africa	115.3	0.11	66.7	0.23	182.0	0.34
North America	107.6	0.25	208.0	0.44	315.6	0.68
Southern Asia	332.5	0.77	92.5	0.77	425.0	1.54
Sub-Saharan Africa	13.8	0.01	85.9	0.59	99.7	0.61
Western Europe	28.0	0.11	44.7	0.25	72.7	0.36
Global	847.6	2.88	760.3	5.00	1607.8	7.88

note. Derived from rosa et al. (2018)

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