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Sustainable irrigation and climate feedbacks

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Agricultural irrigation induces greenhouse gas emissions directly from soils or indirectly through the use of energy or construction of dams and irrigation infrastructure, while climate change affects irrigation demand, water availability and the greenhouse gas intensity of irrigation energy. Here, we present a scoping review to elaborate on these irrigation–climate linkages by synthesizing knowledge across different fields, emphasizing the growing role climate change may have in driving future irrigation expansion and reinforcing some of the positive feedbacks. This Review underscores the urgent need to promote and adopt sustainable irrigation, especially in regions dominated by strong, positive feedbacks.

Irrigation expanded substantially across the globe in the twentieth century, contributing to increased crop productivity[1]. Without irrigation, global cereal production on irrigated lands would decrease by nearly 50% and total cereal production would decrease by 20% (ref. 2). Irrigation is expected to continue expanding, partly to meet increasing food demand, but notably to improve the adaptability of crop systems to climate change and variability[3,4].

The expansion of irrigation might have important consequences for the climate system on global and local scales through greenhouse gas (GHG) emissions and biophysical pathways. Irrigation causes GHG emissions from energy use and facility construction[5–7]. It can also directly affect nitrous oxide (N_2O), methane (CH_4) and soil carbon emissions from cropland, and indirectly induce these emissions from canals and reservoirs constructed for farm irrigation[8,9]. In addition, irrigation has a local cooling effect that is well documented in the hydroclimatic literature[10]. Another potentially beneficial effect of irrigation on climate change is that by improving crop yields, irrigation can spare natural environments from being cleared for crop production[11,12].

Climate change, on the other hand, also affects irrigation. Shifting precipitation patterns, for example, can drive irrigation expansion, but also impact the water and energy systems in which irrigation is embedded. As climate change continues to intensify[13,14], it is crucial to understand how it impacts irrigation and consequently how irrigation-related activities may feed back to the climate system. These impacts can augment the total GHG emissions of the irrigation system and result in potentially meaningful positive climate feedbacks. Overall, these bidirectional feedback loops have not yet been articulated in the large and growing literature on the food–energy–water nexus[15].

Here, by reviewing studies published over the past decade, we synthesize the various irrigation–climate linkages (Fig. 1); evaluate the impacts of climate change on irrigation systems, including irrigation infrastructure and the food–energy–water systems in which it is embedded; and identify areas in which climate change may intensify irrigation-related GHG emissions. Further, we present emerging and innovative solutions that can facilitate the development of sustainable irrigation under climate change. We close by discussing knowledge gaps and future research needs and priorities.

Climate impacts of irrigation

Energy use and associated GHG emissions

Irrigation activities can produce GHG emissions directly when pumps run on diesel or natural gas, or indirectly when pumps use electricity.

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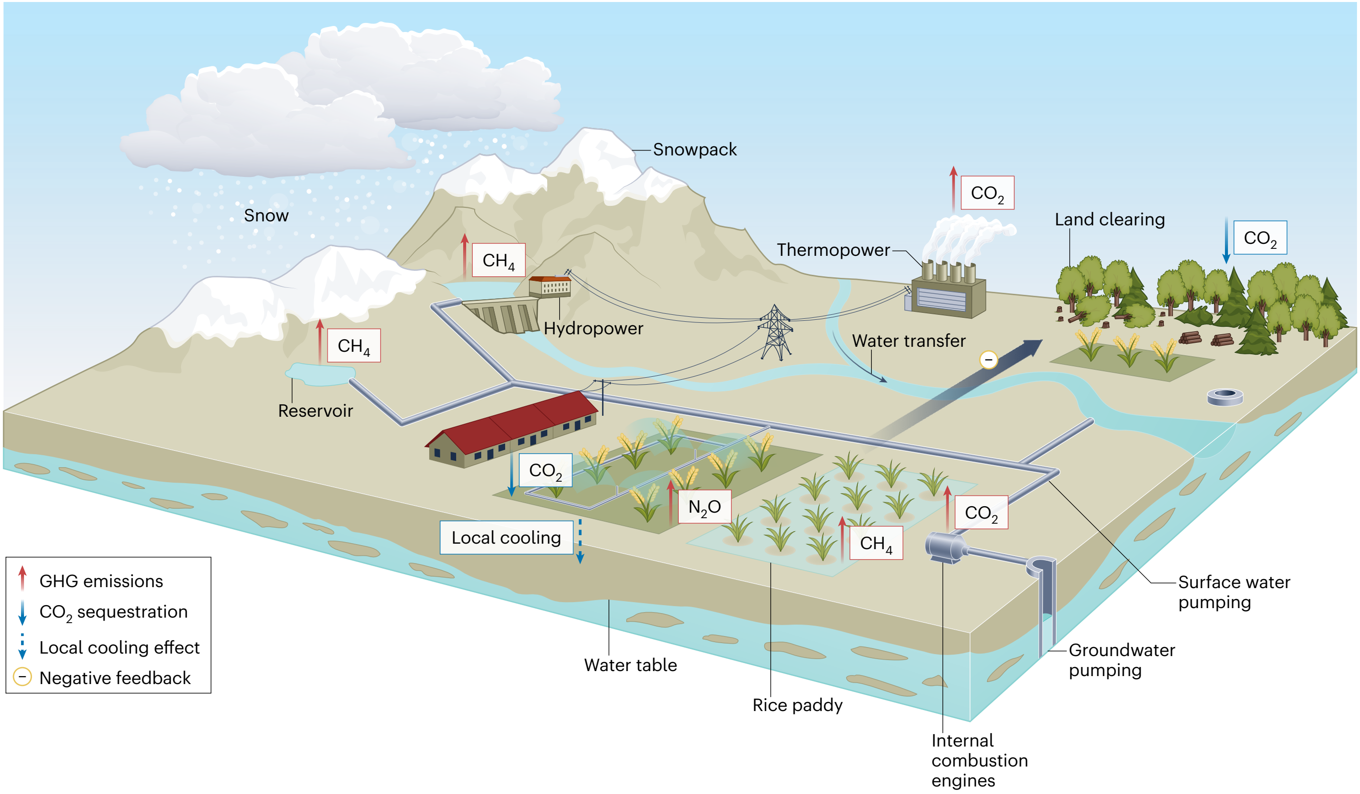

Fig. 1 | Illustration of the climate impacts of irrigation. Direct and indirect GHG emissions (or savings), as well as local cooling effects, associated with a conventional irrigation system that uses a mix of groundwater and surface water (partly transferred from other basins), and runs on internal combustion or electric engines with electricity sourced from hydropower and thermopower. The climate impacts of irrigation can be local (by affecting local temperatures and cropland biogenic GHG emissions), regional (by affecting electricity generation or interbasin water transfer) and global (by affecting land use elsewhere through crop yield changes).

If powered by electricity, the carbon intensity of irrigation depends on the fuel mix of the regional grid; a higher share of fossil fuels in the grid would yield a greater carbon intensity. Additionally, water source is a critical factor of irrigation-associated energy use and emissions. Pumping groundwater is generally much more energy intensive than pumping surface water because of the additional lift needed (for example, 2,100–4,000 KJ m^{-3} versus 3–4 KJ m^{-3} in the Lower Indus Basin of Pakistan[6]). Owing to its ubiquity and consistency, global groundwater use for irrigation has increased substantially in the twentieth century and now supplies ~40% of all irrigated area[16]. Irrigation water can also be transferred from other basins. Depending on the distance and elevation change, the energy intensity of interbasin water transfers can be very high (for example, twice that of groundwater in a case from China[17]). Interbasin water transfers have also seen substantial growth, and currently dozens of large-scale water transfer projects are planned or under construction globally, with the majority intended for irrigation use[18].

Biogenic emissions

In addition to energy-related emissions, irrigation affects fluxes of CH_4, N_2O and CO_2 from croplands. Irrigation, particularly in flooded rice production, is an important driver of global CH_4 emissions due to the anaerobic conditions it creates that favour methanogenic bacteria. Research shows that continuous flooding leads to twice the CH_4 emissions as intermittent flooding[19]. Irrigation also increases N_2O emissions by increasing soil moisture and, consequently, stimulating the nitrification and denitrification processes that produce soil N_2O emissions[8]. Field-scale comparisons show that N_2O emissions can increase by 50–140% in irrigated versus non-irrigated fields, although the magnitude of change depends on many factors such as N application rates, soil properties and irrigation intensity[20]. On the other hand, irrigation may increase soil carbon storage when it increases plant productivity and hence litter into the soil[8]. However, higher moisture due to irrigation also stimulates plant decomposition, resulting in CO_2 emissions[8]. On average, irrigation enhances soil organic carbon storage in arid and semi-arid areas, not in humid environments, with larger increases tied to lower initial carbon stocks and less precipitation[8]. However, site-level effects of irrigation on soil organic carbon are mixed[8,20,21] and depth-dependent[22], and effects on inorganic carbon stocks are relatively understudied despite being an important component of total carbon stocks in many agronomic systems.

Beyond on-farm emissions, additional GHG emissions are incurred from human-constructed bodies of water that transport and store water for irrigation (for example, canals and reservoirs). In the past century, the number of reservoirs for irrigation grew considerably, resulting in an approximately 25-fold increase in irrigation water supply (from 18 to 460 $km^3\ yr^{-1}$)[23]. Irrigation reservoirs vary in size, and building large dams requires a particularly substantial amount of carbon-intensive materials such as concrete. The emissions embedded in materials can be partially offset when the dams generate hydropower. However, water competition in cases of reduced precipitation or irrigation expansion could reduce hydropower output[24], which might result in greater thermal power generation. Regardless, artificial reservoirs can release significant amounts of GHGs by converting organic matter in the flooded areas into CH_4, CO_2 and N_2O, and also by increasing CH_4 bubbling from sediments[25]. A recent study identified CH_4 from reservoirs as a main contributor to the carbon footprint of irrigation in Spain[26]. The impacts of irrigation on GHG emissions and other environmental issues may be reconciled and mitigated by optimizing the siting of reservoirs, as shown in a study of Amazonian hydropower dams[27].

Biophysical feedback

Irrigation can modify local or regional temperature and humidity through multiple biophysical mechanisms[28]. By increasing the availability of water to vegetation, irrigation raises evapotranspiration and the associated latent heat flux. This process lowers air temperature because more energy is used for water vaporization rather than heating the air. However, higher evapotranspiration and humid atmosphere resulting from irrigation tend to foster increased cloud cover, which reflects more shortwave radiation and leads to further cooling, but also amplifies the local greenhouse effect and may contribute to heat stress[29,30]. During the daytime, the dominance of increased latent heat flux among these contrasting effects often leads to a net cooling effect of irrigation[10,31,32]. For example, a recent modelling analysis suggests that crop canopy temperatures can be as much as 10 °C lower than ambient air temperature under well-irrigated conditions[33]. In the Indo-Gangetic Plain, air temperatures in irrigated croplands are significantly cooler than in non-irrigated areas by up to 1–2 °C during the crop-growing season, as inferred from satellite observations[31]. By contrast, the effects of irrigation on nighttime temperatures are not well studied, but some evidence suggests irrigation could warm nighttime temperatures by increasing soil heat storage[34] or enhancing the local greenhouse effect associated with increased atmospheric humidity[30], and possibly more than offset the daytime cooling effect[34]. A frontier research area is the investigation of climate teleconnections associated with irrigation[35,36].

As climate change progresses, there is growing concern regarding the escalating risk of humid heat extremes caused by intensified irrigation. Recent studies based on regional or global climate model simulations indicate that irrigation increases wet-bulb temperatures and the frequency of dangerous heat extremes in various regions, including the North China Plain, the central USA and the Middle East[37,38]. Similarly, satellite and in situ observations found that reduced planetary boundary layer height, as a result of irrigation-induced reduction in sensible heat flux, raises humid heat stress in India, Pakistan and Afghanistan[39]. While humid heat extremes may have had minimal impacts on or even enhanced yields in some regions[40], they pose a growing health hazard for agricultural workers worldwide[28].

Reduced incentives for land clearing

Increased crop yields from irrigation can potentially reduce GHG emissions by decreasing incentives for land clearing. Irrigation is critical to plants in arid or semi-arid regions with limited rainfall, but even in humid regions, irrigation can increase crop yields by compensating for seasonal rainfall variability and deficits[41]. The irrigation-induced cooling effect also contributes to yield gains by mitigating canopy heat stress and atmospheric water demand; for example, a recent study on maize in Nebraska shows that 16% of yield increase from irrigation can be attributed to the cooling effect, with the remaining 84% due to other physiological benefits of increased water supply[41]. Without irrigation, global cereal production would drop by around 20% (ref. 2), thus requiring more land to meet agricultural demands.

Despite the importance of irrigation to global crop production, the 'land sparing' benefits of irrigation-driven yield increases to global GHG emissions are complex and largely unquantified. Nevertheless, studies across a range of modelling complexities support the notion that agricultural intensification, in general, contributes to decreases in agricultural land use at the global scale, as lower prices reduce pressure for land conversion[11,42,43]. Quantifying the contributions of irrigation to global land sparing would also require accounting for interactions between supply and demand, prices, trade and input substitution using complex economic models subject to considerable uncertainty[44].

The spatial configuration of spared land associated with irrigation is also important to consider, because aboveground and belowground carbon stocks, as well as crop productivity, vary substantially across the globe[45]. Additional mechanisms, including land-use zoning, economic instruments, spatially targeted agricultural investments and voluntary standards or certifications are often needed to proactively link yield increases with the protection of natural ecosystems[46]. Further, the biophysical local climate impacts of land clearing also vary in sign depending on latitude, with substantial local warming from tropical deforestation[47].

Finally, irrigation may be required for the expansion of bioenergy with carbon capture and storage, a pivotal negative emission technology for meeting climate targets[48], with implications for total agricultural land use and land sparing[49]. While irrigation will boost yields of bioenergy crops and decrease land requirements, it may drive water consumption and increase global water stress[50]. In addition, bioenergy has been criticized for diverting crops and land away from the food supply, thus raising prices and stimulating land-use change[51].

Growing impacts of climate change

Greater irrigation demand

Greater irrigation demand, resulting from climate-driven changes in regional precipitation and evapotranspiration, would trigger most of the irrigation-induced climate effects. Even when the total precipitation remains constant or increases, future shifts in subseasonal precipitation variability may spur more droughts and irrigation use[52], although moderately intensified heavy rainfall may offset some drought damage[53]. Rising temperature also increases evaporation of surface water and plant transpiration, and can reduce photosynthetic rates, notably in C3 plants (for example, wheat and soybean). To achieve comparable yields, farmers may respond by increasing irrigation intensity[8].

On a global scale, the net impact of climate change on irrigation demand remains uncertain. Significant uncertainties remain around (1) how arid lands (a quarter of Earth's surface) will respond to increases in irrigation; (2) how humans will use irrigation as an adaptation to climate change; and (3) to what extent elevated CO_2 concentrations can mitigate irrigation needs. The effect of CO_2 has been an area of intense research. For example, one study noted an 8–15% global irrigation reduction by the end of the century with elevated CO_2, compared with a 0–5% rise without factoring in CO_2 (ref. 54). Similarly, another study identified net decreases in irrigation demand using the LPJmL model with CO_2, despite regional increases due to local climate change patterns[55]. However, more recent field experiments have found that elevated CO_2 can increase the photosynthesis as well as canopy size for C3 crops, which counteract the water savings from lower stomatal conductance[56]. Thus, additional irrigation may be needed to fully realize the productivity benefits of elevated CO_2 for many major staple crops[57,58], although the net climate outcome remains to be investigated. Indeed, satellite observations have shown a global decline of the CO_2 fertilization effect on vegetation productivity since the 1980s, probably as a result of changes in terrestrial water storage[59].

Despite uncertainties around changes in irrigation water demand, it is clear that many agricultural regions will face climate challenges relevant to irrigation, including decreases in soil moisture[60], rising vapour pressure deficit[61], and changes in the magnitude and timing of surface water availability for irrigation, particularly in snow-dependent basins[62]. Even if climate change elicits a net-zero impact on future global irrigation use, it might ultimately increase total irrigation-induced energy use and carbon emissions due to a shift towards water sources that are more energy intensive or carbon intensive, such as groundwater or reservoirs, as discussed below. This could more than offset the energy saved in wetter places projected to require less irrigation in the future.

Greater reliance on groundwater

Increases in overall irrigation demand or decreases in surface water availability from changes in hydrological cycles can increase reliance on more energy- and carbon-intensive water sources (for example, from groundwater and interbasin transfers). In particular, climate change is likely to exacerbate the need for groundwater use[63] by reducing precipitation in some regions and decreasing summer flows in snowmelt-dominated basins[64]. In California, groundwater, critical to agricultural and economic resilience, constitutes 40% of total water use in wet years and 60% in droughts[65]. Similar substitutions of groundwater for surface water have been observed in other regions due to hydroclimate variability[66].

Irrigation using groundwater requires more energy than with surface water — a climate-driven human adaptation that could result in a positive climate feedback (Fig. 2a). This feedback could be further intensified when persistent deficits in annual recharge combine with continuous over-drafting, leading to lower groundwater levels and higher energy costs of pumping[67]. In Punjab, India, groundwater use increased by 23% and the water table dropped by 5.47 m during 1998–2012, resulting in a doubling of annual carbon emissions[68]. In addition, groundwater contains CO_2 and N_2O because of its interactions with subterranean environments such as soil, minerals and bacteria. When exposed to the atmosphere, these GHGs are released or degassed. The magnitude of the degassed GHGs depends on the properties of groundwater, but is probably small compared with other sources of agricultural GHG emissions[69,70].

Severe groundwater depletion in regions reliant on heavily overexploited aquifers can lead to eventual abandonment of irrigation[54] and/or stricter regulation on inefficient pumping[71]. These responses may cause their own climate impacts. For instance, irrigation abandonment may reduce local cooling effects and subsequent yield decreases may increase pressure for land conversion elsewhere. Globally, however, the majority of aquifers remain underexploited[72], indicating that substantial opportunity for increased groundwater reliance remains.

Greater GHG intensities of irrigation energy

When irrigation is powered by grid electricity, climate change can also affect the grid system in ways that increase grid GHG intensities (Fig. 2a), thus increasing the life-cycle GHG emissions of irrigation. Of particular concern are changes in the availability of hydropower because of its vulnerability to climate variability. Shifts in the patterns of rainfall, snowmelt and glacier melt can lead to lower annual runoff and consequently lower hydropower output, which may increase the dependency on coal, oil or natural gas thermopower to make up for supply shortages[73]. This climate-driven substitution increases the GHG intensity of grid electricity per kilowatt-hour generated. During the recent drought in Western Europe (2016–2017), Spain's hydropower generation dropped by ~50%, resulting in more thermopower from mostly combined-cycle and coal-fired power plants and 18% additional CO_2 emissions compared with the previous year[74]. Across the western USA, repeated droughts over the past two decades have led to increased power generation from coal and natural gas, and substantially increased CO_2 and other air emissions[75]. Increased precipitation and runoff, on the other hand, could create a negative climate feedback by increasing hydropower output, but too much water could result in equipment damage, outage and dam repairment[76], potentially offsetting the climate benefit from the negative feedback.

In much the same way, expansion of irrigation can increase grid GHG emissions, owing to the competition for water. Globally, about half of hydropower capacity competes with irrigation[24]. In these regions, irrigation expansion can reduce the amount of water available for hydropower use and lead to more fossil-fuel-based power generation. Furthermore, climate change can significantly exacerbate water competition among irrigation, hydropower and thermopower (as in prolonged and intense droughts), resulting in greater use of groundwater by both irrigation and energy, higher thermoelectric output and, consequently, substantially higher system-wide energy and carbon intensities than without climate change.

Increased biogenic emissions

Climate change can also increase the biogenic emissions associated with irrigation directly and indirectly. First, temperature and water interact to positively affect soil N_2O emissions. Thus, the N_2O emissions intensity of irrigated cropland might increase as temperature increases[77], all else being equal. Second, climate change is projected to intensify CH_4 emissions from rice paddies owing to both warming and elevated CO_2 levels. Warming increases the rates of plant root decay and soil organic matter decomposition, which stimulates the growth of methanogenic bacteria[78]. A 1 °C of rise in temperature has been estimated to increase rice CH_4 emissions by ~10% (ref. 79). Elevated CO_2 promotes rice root growth and root exudates, resulting in more carbon sources for methanogenic bacteria[79]. Research shows that elevated CO_2 levels (550–743 ppm) may increase rice CH_4 emissions intensity by 30–40%, although the effect can be moderated by incorporation of straw into rice fields[79].

Third, reservoirs, like groundwater, are an important source to help agriculture adapt to hydroclimatic change and variability. Climate change is projected to increase the demand for reservoirs, especially in regions projected to experience reduced rainfall and snowpack[80]. However, not only may the number of reservoirs grow, but higher temperatures will also increase the intensity of biogenic emissions per reservoir (Fig. 2b). Warming increases the rates of aquatic plant decay and soil organic matter decomposition, which, in turn, stimulates the growth of methanogenic bacteria[78]. For irrigation reservoirs that are eutrophic, which are quite common worldwide[81], warming may also aggravate the emission of GHGs, particularly CH_4. In eutrophic reservoirs, excess nutrients already fuel algae growth and decomposition, which creates an oxygen-poor condition that favours methanogenic bacteria[82], and warming will intensify this process by further stimulating algae growth[83]. Studies suggest warming could increase CH_4 emissions intensity from lakes globally by 13–40% by the end of this century[84]. Moreover, climate change may increase the extent of eutrophication among reservoirs, owing partly to increased runoff resulting from shifts in precipitation and partly to increased temperatures, further intensifying the process of CH_4 production.

Sustainable irrigation solutions and innovations

That climate change may intensify the climate impacts of irrigation underscores the urgent need to accelerate the development of sustainable irrigation. Various strategies have long been promoted, including enhancing efficiency with drip systems, improved scheduling, leakage reduction and adopting conservation practices. The wide-scale adoption of these strategies will moderate the projected increase in overall irrigation water use and the number of irrigation-oriented reservoirs needed. Here, we emphasize challenges and tradeoffs involved in some of the innovations that have recently emerged. Promoting these strategies is especially important in regions vulnerable to positive climate feedbacks, aridity, increased groundwater reliance, heightened water resource competition between irrigation and energy, and extensive rice cultivation.

Reduce biogenic CH_4 and N_2O emissions

The potency of CH_4 and the significant contribution of flooded rice paddies to global CH_4 emissions, together with the potential intensifying impact of climate change, highlight the urgency to reduce CH_4 emissions from rice production. But existing GHG mitigation methods often involve tradeoffs. For example, intermittent flooding (for example, midseason drainage) can effectively depress CH_4 emissions from rice fields — as well as water use[85]— and hence is a potentially important climate adaptation strategy. But it might also increase soil N_2O emissions[86]. Straw incorporation can largely moderate the impact of elevated CO_2 levels on rice CH_4 emissions, but the straw itself is also a source of GHG emissions[79]. Reducing rice CH_4 requires a systems

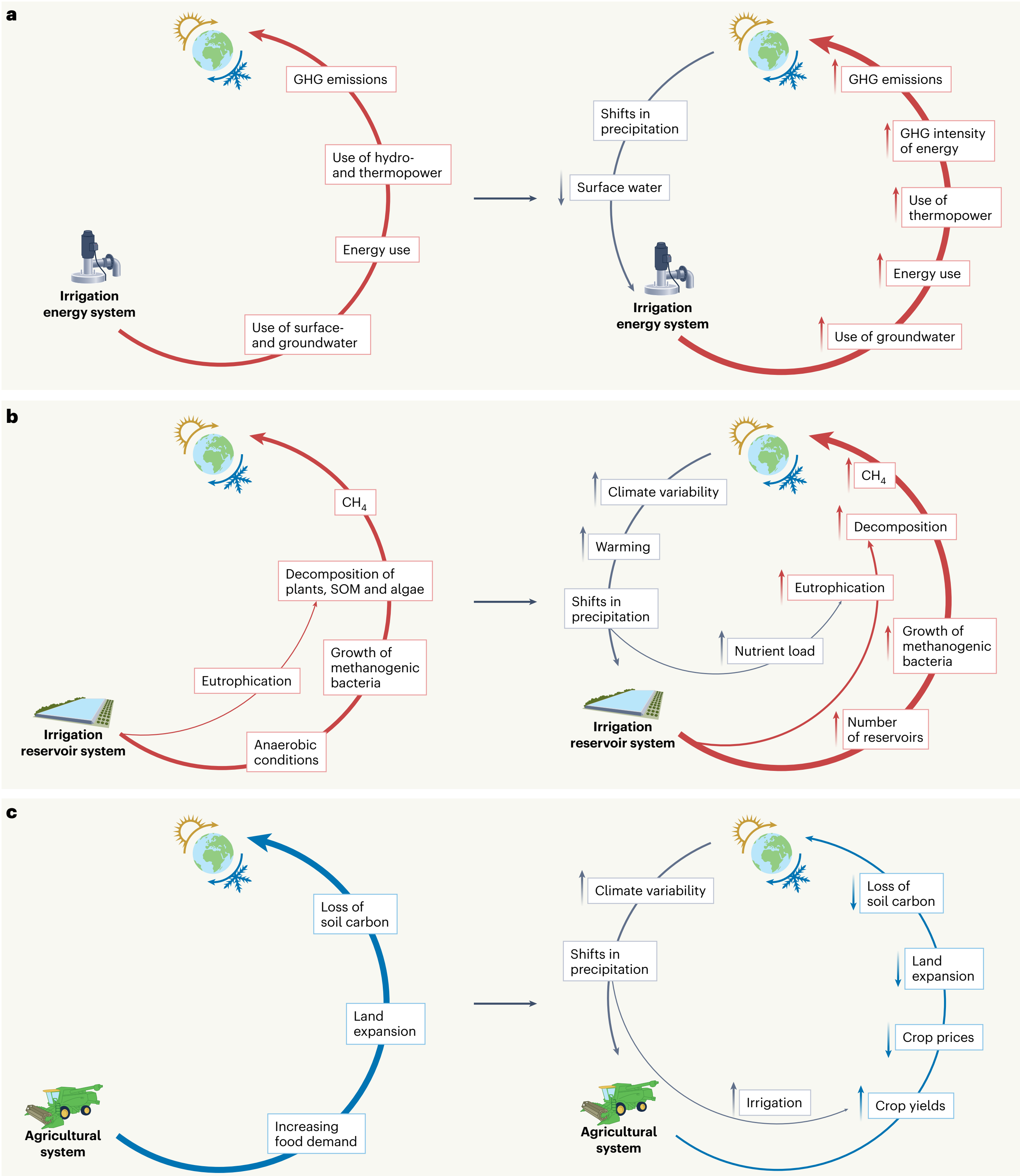

Fig. 2 | Conceptual models of climate–irrigation feedbacks. a–c, Climate change can increase GHG emissions from irrigation energy systems (**a**) and irrigation reservoir systems (**b**), and reduce GHG emissions through increasing crop yields (**c**). Panels on the left indicate mechanisms by which irrigation or agriculture induce GHG emissions under a relatively stable climate. Panels on the right indicate how climate change affects these mechanisms and leads to greater or lower GHG intensity of irrigation (represented by the thicker or thinner arrows, as opposed to those on the left). SOM, soil organic matter.

approach that manages multiple factors simultaneously to minimize these tradeoffs[86]. Emerging technologies such as biochar application may also be helpful[87]. In other crop systems, switching from furrow or sprinkler irrigation to drip irrigation — which reduces the extent of denitrification via partial wetting of soils[8] — can decrease soil N_2O emissions by 32–46% (ref. 88). Irrigation coupled with conservation tillage can also increase soil organic carbon sequestration compared with conventional tillage[8].

The increasing demand for irrigation-oriented reservoirs and water transfers in response to climate variability and change presents challenges as well as opportunities. Opportunities arise with new reservoirs as they can be designed to minimize potential GHG emissions. Measures to mitigate emissions include limiting the input of nutrients and organic matter, avoiding a rapid drawdown (which promotes CH_4 emissions), and increasing oxygen concentrations in the water[9]. Covering reservoirs or canals with solar panels can deliver carbon, water and land benefits[89] (see some examples from California in Fig. 3). Irrigation reservoirs covered by floating solar energy with some power clipped to run an aerator have been shown to help reduce GHG emissions via reduced water temperature and increased dissolved oxygen[90]. Large reservoirs covered by solar panels can produce substantial amounts of energy, but there are potential tradeoffs – for example, effects on aquatic biota and terrestrial wildlife, and on the ecological and recreational values of reservoirs – that must be considered and minimized[89]. Large reservoirs with high GHG emissions can be monitored and involved in carbon credit programmes, which provide financial incentives for mitigation. Freshwater systems such as reservoirs, lakes and ponds are now receiving increasing interest and becoming targets of national GHG mitigation commitments.

Power irrigation with renewables

The reciprocal feedback between climate change and irrigation necessitates the expansion of low-carbon irrigation. Diesel- and gasoline-powered irrigation engines, although less efficient than electric ones, are still widely used globally[91]. Irrigation electrification, alongside grid decarbonization, can reduce energy consumption and GHG emissions. However, large-scale clean electricity implementation poses challenges and may not benefit off-grid smallholders in remote areas. For them, the strategy is to install renewable energy generators such as solar-, wind- and water-powered pumps. The selection of renewable sources should adapt to site-specific hydrological and socioeconomic conditions and align with the temporal needs of agricultural production.

Widespread adoption of renewable pumps will depend largely on cost reduction, power purchase agreement decisions, innovative business models and long-term community promoter presence[92]. De-risking investments for development partners and unbanked smallholders is a key area to prioritize, as financing these systems will support climate change mitigation and safeguard vulnerable farmers' livelihoods. When there is social cohesion, group-based pump sharing can facilitate access to finance for the initial capital investment, especially for poor farmers. In many sub-Saharan regions, solar pumps may not be cost-effective within a 25-year period without monetizing environmental benefits[93], thus requiring new microfinancing mechanisms. Cases with preliminary success were achieved by using Internet of Things and mobile payments technologies to offer flexible payment plans as a way to align payments with farmers' income patterns[94]. GHG reductions from switching to renewable pumps in poor countries can be monetized and, if compensated by rich countries through financial transfers, could facilitate the adoption of renewable pumps in those countries.

To avoid over-abstraction of groundwater that can emerge from reduced irrigation operational costs, renewable pumps should be integrated into strong regulatory frameworks on sustainable water resource use. Feasibility studies for renewable-powered irrigation systems often focus on technical and economic aspects but lack an assessment of water resource availability and impact. However, a drop in groundwater levels, caused by either climate change or overexploitation, can negatively affect agricultural productivity and economic feasibility of those renewable irrigation systems. Opportunities do exist when on-farm generated renewable energy is used for other purposes, encouraging farmers to make rational decisions about pumping. In western India, a grid-connected scheme has been implemented to buy back surplus solar power from farmers to prevent excessive withdrawals[95]. Besides financial incentives, educating on integrated soil, water and energy management is vital for system viability[96]. Addressing climate risks in climate-vulnerable regions[97] is also crucial for minimizing downtime and asset loss of renewable pumps.

Create techno–ecological synergies

Beyond providing electric power, on-farm solar energy can be designed to facilitate techno–ecological synergies that deliver broad benefits to humans and nature. Such systems can maintain crop yields while generating benefits, including reduced irrigation water consumption and reduced GHG emissions associated with water pumping. For example, agrivoltaics are a techno–ecological synergy that co-locates solar energy and crop production[98]. In northwestern India, modelling demonstrated that water inputs for cleaning solar panels are the same as those required for annual aloe production, such that the co-location of solar panels and aloe may yield higher returns per cubic metre of water than either system alone[99]. Agrivoltaics may reduce evapotranspiration, retain more soil moisture and hence reduce irrigation demand due to altered microclimatic conditions by solar arrays[100]. The partial shade of solar panels may also provide a cooling effect for crops underneath agrivoltaics systems and bolster yield[100]. Adoption remains low for agrivoltaics; however, governments including China, France, Germany, Japan and the USA have supported agrivoltaics development via research investments as well as regulatory permitting pathways and/or incentives.

Solar energy production on marginalized and abandoned farmland, as well as on reservoirs[89], may spare prime agricultural land with comparatively moister and less saline soils[101], and facilitate carbon sequestration, especially when coupled with sustainable development practices such as revegetation and soil amendments (for example, biochar)[102], leading to a climate feedback loop with potentially lower irrigation demand and GHG emissions. Additive solar energy in agricultural landscapes may be developed in lands adjacent to farmland and in the negative space (that is, uncultivated areas) of agricultural fields. The groundcover, interspace and borders of ground-mounted solar energy facilities adjacent to agricultural land may be restored with plants comprising pollinator habitat[103], which can increase pollination services in nearby agricultural fields (for example, within 1.5 km)[104] that may act in conjunction with abiotic factors, including water stress, to affect crop yield. Additionally, farmers can develop solar energy, underlaid by native pollinator habitat[104], in the corners of agricultural fields irrigated with centre-pivot technology to make use of unirrigated, negative space[105] that may bolster food system resilience, biodiversity conservation and land sparing – outcomes that address climate change and biodiversity goals without additional land resources[106].

Implications and outlook

In this Review, we elaborate on the various climate–irrigation feedback loops and identify areas where climate change may tilt the scale by amplifying some positive feedbacks of irrigation via producing more GHG emissions directly or indirectly. It is especially important to understand these feedback effects in regions constrained by freshwater resources, as different adaptation strategies have very different climate implications. In cases where irrigated croplands revert to rain-fed croplands or grazing lands, crop yields will decline, which might result in indirect land-use change and associated carbon loss. A top priority for future research is to quantify both the contribution of agricultural irrigation to global GHG emissions and the feedback effects due to the changing climate at local and global scales. Global estimates that take into consideration the multiple mechanisms reviewed here are currently lacking but could be potentially large.

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Fig. 3 | Examples of floating photovoltaics. a, A floating photovoltaic system around the University of California at Davis designed to reduce green algae by improving aeration with solar energy. **b**, A floating solar farm producing clean renewable electricity energy and reducing reservoir evaporation in Flevoland, the Netherlands.

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Our Review underscores the need to develop an integrated framework around irrigation in future irrigation research and management. An integrated framework can help researchers and planners (1) identify the relative strength and Earth system relevance of various feedbacks; (2) identify climate hotspots, that is, where changes in local or regional climate may necessitate additional irrigation infrastructure and intensify some of the positive climate feedbacks; and (3) prioritize strategies to better harvest the climate benefits of irrigation while minimizing its negative consequences. Such an integrated framework can, for example, help decision-makers invest in irrigation means that are more sustainable, considering the potential feedback loops.

More broadly, greater attention should be paid to climate change in the rapidly growing food–energy–water literature. As climate change intensifies, there is an urgent need to understand not only the effectiveness of different adaptation and mitigation strategies but also how they would feed back to climate change. The integrated nexus thinking and modelling in the food–energy–water literature can be expanded to climate–food–energy–water. This climate-integrated thinking can help us build more climate-resilient food–energy–water systems and better identify opportunities for adaptation and mitigation synergies.

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Author contributions

Y.Y., Z.J. and N.D.M. conceived and designed the experiments, analysed the data and wrote the paper. A.W.D., R.R.H., S.M.G., L.L.S., M.V.C., Y.-G.Z. and D.B.L. contributed materials and wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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