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Review article

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Irrigation in the Earth system

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Abstract

Irrigation accounts for ~70% of global freshwater withdrawals and ~90% of consumptive water use, driving myriad Earth system impacts. In this Review, we summarize how irrigation currently impacts key components of the Earth system. Estimates suggest that more than 3.6 million km^2 of currently irrigated land, with hot spots in the intensively cultivated US High Plains, California Central Valley, Indo-Gangetic Basin and northern China. Process-based models estimate that ~2,700 ± 540 km^3 irrigation water is withdrawn globally each year, broadly consistent with country-reported values despite these estimates embedding substantial uncertainties. Expansive irrigation has modified surface energy balance and biogeochemical cycling. A shift from sensible to latent heat fluxes, and resulting land–atmosphere feedbacks, generally reduce regional growing season surface temperatures by ~1–3 °C. Irrigation can ameliorate temperature extremes in some regions, but conversely exacerbates moist heat stress. Modelled precipitation responses are more varied, with some intensive cropping regions exhibiting suppressed local precipitation but enhanced precipitation downstream owing to atmospheric circulation interactions. Additionally, irrigation could enhance cropland carbon uptake; however, it can also contribute to elevated methane fluxes in rice systems and mobilize nitrogen loading to groundwater. Cross-disciplinary, integrative research efforts can help advance understanding of these irrigation–Earth system interactions, and identify and reduce uncertainties, biases and limitations.

Sections

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Introduction

Irrigation is a critical component of land and water resource management, accounting for ~70% of freshwater withdrawals[1–3], that is, water abstracted from a ground or surface freshwater reservoir and conveyed to a place of use. Additionally, irrigation is responsible for 84–90% of annual global freshwater consumption (withdrawn water that is evaporated, transpired, incorporated into products or crops, or consumed by humans or livestock), or ~1,200 km^3 of water, with ~545 km^3 being sourced from groundwater[1,4,5]. Irrigated fields cover ~20% (~3.5 million km^2) of global croplands, and these areas produce ~40% of the world's food (according to the United Nations Food and Agriculture Organization (UN FAO))[5].

Irrigation is also a complex driver of regional environmental change, which has consequences for process-based modelling[6–8]. Although irrigated lands occupy only ~2.5% of global land area, irrigation drives groundwater depletion[9], enhanced soil salinity and nutrient leaching in agricultural systems[9,10] among myriad other environmental impacts[10,11]. Furthermore, rising irrigation demand has intensified water management over the twentieth century, partly driving increased construction of water reservoirs and diversions that also have downstream hydrological impacts[11,12]. Applied irrigation water also impacts regional hydroclimates both locally, through feedbacks on temperature, humidity and precipitation[13,14], and remotely through complex interactions between altered temperature and moisture gradients and larger-scale processes such as atmospheric circulation and wave activity[15]. These changes can even affect heat extremes in both agricultural and urban areas[16] and biogeochemical cycling[17]. Demand for irrigation will continue to rise throughout the twenty-first century[18,19], primarily for agriculture but increasingly for urban landscapes as well. These trends, alongside climate change-induced water disruptions, put pressure on existing irrigation water supplies and might drive some regions into water scarcity[20,21].

Despite constituting a socio-ecological system with many important and non-linear feedbacks and interactions, irrigation remains largely underrepresented or nascent in process-based models, in particular climate, crop, hydrological and biogeochemical cycling models. The suboptimal representation of irrigation in models is problematic because both climate change and water demand trends are altering continental water cycling[11]. Model limitations and uncertainties make it challenging to systematically explore and disentangle the influence of irrigation from other factors driving global environmental change, and thus it is also difficult to project the hydroclimate impacts of irrigation in the future[22]. Improved irrigation data are required, in part, to represent important irrigation characteristics in process-based models, such as the existing heterogeneity of irrigation management across space and time including the timings, quantities and application systems used. Such models will lead to a deeper understanding of irrigation feedbacks and interactions with Earth system components and processes. Progress on these fronts can further aid the development of potential irrigation scenarios, and assessments of how these scenarios interact with climate change and socioeconomic development to impact Earth system processes, hydrological cycling and ecosystem services (for example, food production and environmental flows).

In this Review, we outline the current understanding of the interactions between irrigation and Earth system components and processes through an interdisciplinary lens, including inputs from data and observations, climate, agriculture and water resources research communities. We first describe how irrigation is estimated with both empirical data and models, and review the current global extent and amount of irrigation water use. Next, we discuss the current conceptual understanding of irrigation–Earth system interactions and indicate where specific regional impacts have been identified with observations and models. We further consider how future climate change and socioeconomic development will impact irrigation trends and irrigation–Earth system interactions, as well as exploring potential sustainable water use scenarios. Finally, we suggest immediate next steps for cross-disciplinary irrigation research to identify and address key sources of uncertainty and model limitations, and improve the characterization of complex irrigation–climate interactions and how these interactions might evolve in the future.

The current state of irrigation

Knowledge of the current state of global irrigation is informed by a combination of official statistics, remote sensing products and state-of-the-art process-based models. Together, these approaches reveal the rapid pace of global irrigation development.

Irrigation estimates from census and remote sensing products

Reported agricultural census data provide some information on irrigation water use, typically at coarse spatio-temporal resolutions. Most widely reported are statistics on irrigated area, either area equipped for irrigation or area actually irrigated. These data sets combine census, survey and/or satellite remote sensing data to represent the irrigated area for a given time period. Importantly, irrigation data obtained using census surveys rely on farmer and/or water manager responses and could, therefore, embed systematic overestimates or underestimates depending on incentive structures and/or monitoring capacity. As such, it can be difficult to ascertain the accuracy of any reported estimates (Box 1).

At the national scale, irrigated area data are provided by international organizations such as the UN FAO, which collates country-reported statistics in the FAOSTAT and Aquastat databases[23] (Fig. 1). Countries with some of the world's most intensively cultivated areas — including China, India, the United States and Pakistan — report the area actually irrigated at national and subnational scales. These statistics can be further disaggregated into different irrigation sources (for example, groundwater versus surface water) and delivery systems (for example, sprinkler, flood or drip).

Some census data also report irrigation water withdrawals. The UN FAO provides 5-year estimates of irrigation withdrawals at the country level, but these data do not include details on how much water is applied to croplands or how much is consumptively used; withdrawals might also be underreported by some countries. Some countries report finer-scale irrigation water withdrawal data, for example, the US Department of Agriculture (USDA) and US Geologic Survey estimate irrigation withdrawals at the county scale at 5-year intervals[24]; the Pakistan Bureau of Statistics reports irrigation water withdrawn from canals at the province scale; and the China Water Resources Bulletin reports withdrawals for agriculture at the province scale[25]. India does not report similar withdrawal data, but the Central Ground Water Board and the Directorate of Economics and Statistics provide ancillary data that can be used to estimate withdrawals including irrigated area, irrigated fraction by crop type and groundwater depth measurements from test wells across the country.

Beyond census statistics, advances in satellite remote sensing have enabled regular gridded (increasingly with grid sizes of less than 1 km) geospatial analyses of irrigation, which help resolve patterns and interactions at the landscape level. For example, the wide availability of data

Box 1

Outstanding uncertainties in irrigation data and modelling

Major uncertainties and gaps remain in irrigation research. High-resolution spatio-temporal data sets of the area actually irrigated annually, crop species and calendars, irrigation methods, amounts and timing are critical to model irrigation[210]. However, no large area data sets exist for all these parameters. Furthermore, uncertainties in existing irrigated area estimates, a critical input for irrigation models, introduce large variation in irrigation predictions that might be partly irreducible[186]. The irrigation research community could therefore consider the 'limits of acceptability' for incorporating current data uncertainty into model frameworks[157,211].

Without reliable data constraints, model-implemented irrigation lacks accuracy, and disparate model irrigation schemes and parameters (such as target soil moisture and irrigation efficiencies) lead to non-negligible variation in simulated irrigation water withdrawals and consumption[53,55,210,212,213]. Additionally, although more hydrological models are being developed with groundwater and river-routing representations[11,52,172,208], challenges remain in accurately allocating irrigation water withdrawals to surface water and groundwater resources.

The simulation of crop growth, including evapotranspiration, phenology and cropping calendars, and water and nutrient limitation, can also contain myriad uncertainties that require systematic characterization[214,215]. Most models do not represent spatio-temporally detailed water infrastructure and management, including reservoir operation, inter-basin transfer and managed aquifer recharge[208]. Overall, differences in model irrigation schemes, coupled with differences in model surface climate sensitivities, can drive large variations in the simulated irrigation–climate interactions within and across models.

Some aspects of model development can make it more challenging to understand irrigation–Earth system interactions. For example, model intercomparisons are helpful to identify commonalities and differences in responses, but the expense of running models and the need to control model heterogeneity in protocol design remain sizable challenges[190,191]. Although there can be high levels of inter-model variation when simulating irrigation–Earth system interactions, several models nevertheless share common development trajectories, and may not constitute fully 'independent' estimates when comparing models. Additionally, modellers have a tendency to select models that they are most familiar rather than considering the adequacy of a model for particular research questions[191].

Tensions also arise between reductive model representations that focus on key irrigation attributes and approaches that increase the model complexity to add more realistic processes[190]. For example, most current Earth system models (ESMs) represent land–atmosphere flux exchanges based on the whole grid average states at relatively coarse spatial scales (around 100 km)[38,190], omitting important land surface heterogeneity, particularly land management approaches, that can impact surface climate characteristics such as energy and water balance[194]. Representations of sub-surface flows and lateral movement of water are often simplistic and can contribute uncertainties to the prediction of irrigation water availability, particularly in future climate scenarios. Approaches to modelling irrigation water applications and efficiencies also remain naive[47,179,216], requiring improvements in both data and modelling frameworks. However, more accurate inclusions of these processes, which impact many Earth system components, lead to increased model complexity, making the model harder to use and understand[190]. Using multiple model development and evaluation methods could help assess the value of increasing the model complexity and the adequacy of a model for addressing key research questions.

Limitations in irrigation research also stem from gaps between biophysical and human research fields, and between research and practice. Modelling that omits explicit representations of human decision-making might reach unrealistic findings about irrigation performance: people often do not irrigate in agronomically ideal ways. In addition to biophysical conditions, irrigators are influenced by a range of dynamic socioeconomic and political factors that are difficult to capture in biophysical models. This limitation does not, however, make these factors unimportant[217,218]. Crucial differences in irrigators' expectations for water delivery and their capacity to absorb risks can reshape farm system decisions, influencing landscape-scale outcomes such as water consumption and agricultural productivity[171,218–220].

from visible, near infrared and microwave satellite sensors from various satellite missions has led to the development of improved techniques for assessing which areas are irrigated, the timing of irrigation and/or water volumes supplied to the fields[26–32]. These data can all contribute to improving global maps of some irrigation characteristics. Remote sensing estimates of irrigation can vary in their accuracy, with some products, such as irrigated area, being generally validated with high accuracy as they are easily distinguishable using spectral features and do not require data with high temporal resolution[33,34].

However, capturing the timing of irrigation, and retrieving irrigation water volumes, has proven to be more challenging than measuring the irrigated area[30–32,35–37]. The accuracy of the retrieved irrigation information is strongly affected not only by the intrinsic trade-off between the spatial and temporal resolution of the observations but also by factors such as cloud cover and sensitivity to vegetation (concerning microwave acquisitions)[29,31]. For instance, methods to estimate applied irrigation water based on evapotranspiration do not consider the total amount of water applied to the fields or water lost by irrigation systems, runoff or infiltration into the soil beyond 5 cm depths. Observations of soil moisture from traditional microwave sensors (such as the Soil Moisture Active Passive (SMAP) satellite) partly address these issues[38,39] but are limited to resolutions of 10–40 km, making it difficult to separate the irrigation signal of individual fields from other surface water reservoirs such as vegetation water content,

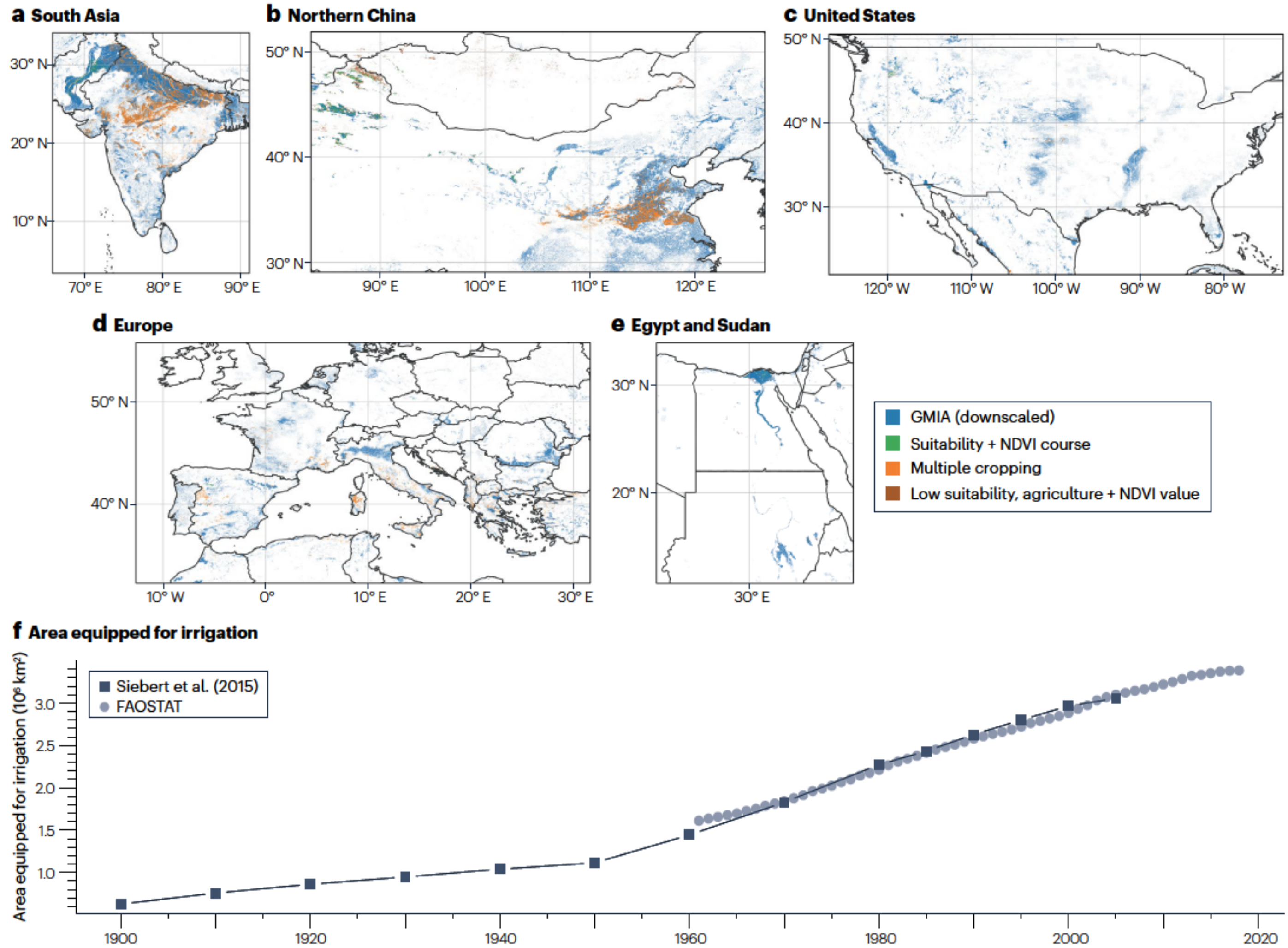

Fig. 1 | Global irrigated areas. a–e, The spatial extent of irrigation[24] with a resolution of 30 arcsec (~1 km at the equator) for India and South Asia (panel **a**), northern China (panel **b**), the United States (panel **c**), Europe (panel **d**) and Egypt and Sudan (panel **e**). Colour scale represents types of irrigated areas: blue, global map of irrigated areas (GMIA) downscaled product[201]; green, irrigated land area identified from agricultural suitability data and remote sensing information of multi-temporal normalized difference vegetation index (NDVI) profiles; orange, irrigated regions in which multiple crops are grown within 1 year; and brown, regions with low agricultural suitability. **f**, Time series of the global area equipped for irrigation[201] and extended to 2020 with United Nations Food and Agriculture Organization (UN FAO) Aquastat. The total global area of irrigation coverage is estimated to be 3,674,000 km^2.

surface topographic variations that lead to open water collection and even fractions of urban areas. Furthermore, SMAP-derived and other similar products do not capture soil moisture in the root zone (~30 cm soil depth), which is critical for plant water uptake, or sub-surface irrigation.

More promising results have, nevertheless, been obtained from the high-resolution Earth observation data of the European Space Agency Copernicus Sentinel programme, which uses sub-kilometre observations of backscatter to assess soil moisture and other observations gathered from thermal, visible and near infrared-based sensors of the Sentinel series satellite[27,28,32,35,40]. At the continental to global scale, gravimetric observations, such as those from Gravity Recovery and Climate Experiment Follow-On (GRACE-FO), can provide indirect estimates of irrigation water withdrawals by measuring changes in the total terrestrial water storage and correcting for variations in water storage caused by other water reservoirs such as glacier ice mass or soil moisture. However, these sensors are constrained by coarse spatial and temporal resolutions[41].

Changes in global and regional irrigation

Long-term time-varying data[23] generally reveal an expansion of irrigation (Fig. 1f), although these data embed uncertainties and regional differences in irrigated area (see Supplementary Table S1). The irrigated area rapidly expanded in the latter part of the twentieth century, reaching a current global irrigated area of ~3,640,000 km^2 (ref. 42) (with the area estimated by various data sets ranging from 3.1 M km^2 to 4 M km^2; see Supplementary Table S1). Despite uncertainties in global totals, there is agreement on the locations of important regional irrigation hot spots, including the Indo-Gangetic Basin (IGB) (Fig. 1a), northern China (Fig. 1b), the US High Plains and California Central Valley (Fig. 1c), Spain, France, Italy, the Netherlands and Romania (Fig. 1d) and Egypt (Fig. 1e).

In some agricultural regions, subnational irrigation data can reveal finer-scale patterns beyond hot spots of activity. For example, Indian agricultural census data report that more than 80% of cultivated land across the Indian IGB is irrigated, although the actual irrigation applied varies seasonally and is at a minimum during the pre-monsoon season throughout April and May[43]. In the US High Plains, the Kansas Water Information Management and Analysis System (WIMAS) further provides records of how irrigation water is being used. In doing so, they demonstrate rapid adoption of low-energy precision irrigation application technologies across irrigated areas, increasing from ~7% in 1996 to 81% in 2016 (ref. 44).

Thus, there is a general understanding of where irrigation hot spots occur, characterized by a high proportional area coverage of irrigation equipment or infrastructure. However, it is not always the case that an equipped area is actually irrigated, due to variability in water availability, infrastructure and type of irrigation system, and other socioeconomic constraints. Improved data for resolving irrigation water management, including satellite retrievals, census data and farmer reporting, would help advance understanding of not just the potential irrigation extent but also how irrigation water is applied across space and time.

Irrigation estimates from process-based models

Outstanding limitations of observational data motivate the use of process-based models to provide spatially explicit and temporally comprehensive information on irrigation water use. As such, irrigation schemes have been incorporated into hydrological and agricultural models, and increasingly ESMs[11,45–47].

The models produce a range of irrigation withdrawal and consumption estimates, with average water withdrawal reaching ~2,700 km^3 year^{-1} with a standard deviation of 540 km^3 year^{-1} (Fig. 2a; see Supplementary Table S2), broadly consistent with irrigation withdrawal estimates from UN FAO Aquastat[48]. Water consumption from irrigation is further estimated at ~1,200 km^3 year^{-1} with a standard deviation of 99 km^3 year^{-1} (Fig. 2b; see Supplementary Table S2). Nevertheless, the accuracy of these estimates should be considered in light of several model uncertainties (Box 1), including structural and epistemological uncertainties, as well as the input data that drive them.

In general, most models estimate irrigation water requirements using either a root-zone soil moisture deficit approach or a crop-specific potential evapotranspiration approach. In the former, irrigation demand is estimated as the amount of water required to maintain root-zone soil moisture, typically within the top metre of the soil, above some threshold during the growing season[38,49–51]. In the latter, irrigation water requirements are estimated either as the difference between crop-specific potential evapotranspiration and the simulated (unirrigated) evapotranspiration or as the difference between potential and effective precipitation[52], usually in well-watered conditions such that crops transpire at the potential maximum rate. Some models also prescribe irrigation area and amounts based on the results of other offline model simulations. In these cases, irrigation is applied at a constant rate for a specified period[14] assuming that all demand is met by available surface water or implicit groundwater sources[11].

Partitioning irrigation water into beneficial components (for example, crop transpiration, microclimate and nutrient management) and non-beneficial components (including soil evaporation, interception, surface runoff, drainage and conveyance losses) is also still a nascent point of development for process-based models[53]. Assessing how much water is beneficially used by crops is challenging, but critical for improving estimates of irrigation water consumption. For example, one estimate using the Lund–Potsdam–Jena managed land (LPJmL) model suggests that only 26% of irrigation water is beneficially consumed (that is, directly transpired by targeted crops instead of being lost by evaporation, interception and/or conveyance) globally[47], although this estimate does not consider the beneficial impacts of irrigation for maintaining microclimate conditions or nutrient management among other model limitations (Box 1). This relatively low rate of beneficial water use is in contrast to the volume of irrigation water abstraction: model estimates of environmental flows indicate that at least 40% (~1,000 km^3 year^{-1}) of current global irrigation water use is unsustainable and occurs at the expense of natural ecosystem requirements[19,54], altering river flows worldwide.

Emerging model developments also include coupling irrigation to surface water reservoir modules to incorporate irrigation water constraints and limitations[50], which can improve representations of regionally specific seasonality in irrigation water allocations[50]. Another notable development in the hydrological modelling community has been the estimation of the volume of irrigation water withdrawn from groundwater and the associated depletion of groundwater aquifers[55–57]. For example, some hydrological (water balance) models link irrigation-induced groundwater depletion to environmental flow limits[58]. Hydrological models with enabled groundwater schemes also estimate that 7–15% of unsustainable groundwater abstractions contribute to downstream crop water requirements and ecological low-flows, which will have implications should withdrawal patterns remain unchanged while irrigation efficiency (the proportion of extracted water that is beneficially consumed) increases or groundwater supplies decrease[58].

Crop and combined crop–hydrological models[59] provide more detailed representations of crop-specific phenology and resource (water and nutrient) use than hydrological models without explicit crop growth representations. Combining the strengths of agronomy-based crop models and physically based Earth system land surface models can also substantially improve simulations of crop growth and yield[59]. Furthermore, the inclusion of CO_2 fertilization has been standardized in crop model experimentation given its effects in modulating crop water productivity, which can modify the irrigation requirements under climate change[60–62]. Most crop models can estimate net irrigation requirements, but not all account for wind and evaporative water losses during application[47,63]. Some models apply fixed global or regional irrigation efficiency values for irrigation applications, but these values do not capture sub-regional spatio-temporal heterogeneity[47]. The amount of irrigation water and the efficiency of its usage is also affected by the choice of irrigation system (for example, sprinkler, drip or flood). Although most crop models assume the use of sprinklers for irrigation due to a lack of reliable global data sets, emerging developments now include a range of irrigation systems and their different efficacies to partition water for various crop types[47]. Nevertheless, model estimates of irrigation efficiency are currently simplistic and in the early stages of development (Box 1); however, such estimates are crucial for estimating the potential savings of reducing non-beneficial water consumption.

Irrigation, climate and the environment

Large volumes of applied irrigation water have biogeophysical and biogeochemical impacts on the Earth system. These regional interactions and impacts are complex and cannot be easily investigated with simplified regression approaches (for example, requiring assumptions of stationarity), thus motivating the use of process-based models. Representing key irrigation–climate interactions in process-based models can reduce modelled hydroclimate biases, making the modelled results more consistent with observations[7,8,64–67].

The biogeophysical and biogeochemical impacts of irrigation

Irrigation increases soil moisture, which impacts surface energy partitioning (Fig. 3), thereby interacting with weather and climate. If soil moisture is low, evapotranspiration or latent heat flux is reduced and more energy is available for sensible heating, increasing near-surface temperatures[68]. Irrigation increases soil moisture, increasing evapotranspiration and lowering the Bowen ratio (the ratio of sensible to latent heat flux) (Fig. 3) to drive near-surface cooling[14].

Additionally, increased irrigation-driven evapotranspiration can raise near-surface humidity, moist static energy and, in some regions, convective available potential energy (CAPE; a measure of atmospheric instability that provides an approximation of updraft strength within a developing thunderstorm)[14] (Fig. 3). This additional atmospheric moisture can also facilitate enhanced cloud cover that, in turn, induces a positive feedback by which enhanced cloud cover reduces incident short-wave radiation and net radiation. This reduction can lead to irrigation having an additional cooling effect at the land surface[14].

Although the cooling effect of enhanced latent heat fluxes is fairly intuitive, irrigation can also increase surface temperatures under certain conditions. First, irrigation-sourced soil water can lower the albedo of the surface, increase net surface radiation and increase thermal conductivity, thereby reducing upwelling long-wave radiation at night[69]. At the same time, some regions can experience increased night-time temperatures owing to locally enhanced atmospheric water vapour caused by irrigation, which increases downwelling long-wave radiation[70]. Whether the cooling or the warming effects dominate depends on a range of conditions, including (but not limited to) the prevailing climate and the degree to which the local land surface influences atmospheric processes[71]. Soil textures and physical properties, seasonal temperature and moisture cycles, and interactions with daily and sub-daily scale boundary layer processes can also mediate local and regional climate responses to irrigation.

Even more complex are the impacts of irrigation on hydrological cycling and precipitation. Enhanced humidity and CAPE increase the possibility of local moisture recycling and convective triggering (Fig. 3) although the resulting precipitation response is uncertain[72]. Irrigation-induced cooling at the land surface can increase atmospheric stability, thereby inhibiting local precipitation. However, near-surface cooling can induce anomalous subsidence and low-level divergence anomalies over irrigated areas, which can interact with the prevailing winds to drive upward motion in remote locations, thereby increasing precipitation likelihoods outside irrigated areas. Enhanced water vapour from irrigation can reside in the atmosphere for up to 20 days before precipitating[73]. Extensive irrigation can even change local and regional thermodynamic gradients and surface roughness by altering vegetation growth, which can influence a range of atmospheric dynamics from local near-surface windspeed[74,75] to larger-scale circulation and, thus, affect the transport of moisture to remote and unirrigated locations[76] (Fig. 3). These exports of water to surrounding areas are not necessarily confined to land – irrigation can also enhance water export to the oceans, thereby contributing to sea-level rise[77].

Irrigation-induced increases in soil moisture facilitate more productive vegetation and increased planting density[78] with greater leaf area. This vegetation response can drive increases in total evapotranspiration fluxes from irrigated croplands, thereby impacting surface energy balance and partitioning[79] (Fig. 3). In addition, intensive agriculture (including improved crop varieties, irrigation and nutrient management) can lead to increased crop biomass that, excluding the harvest index, increases and/or changes partitioning and turnover in agroecosystem carbon and nitrogen pools[80]. Increased crop biomass,

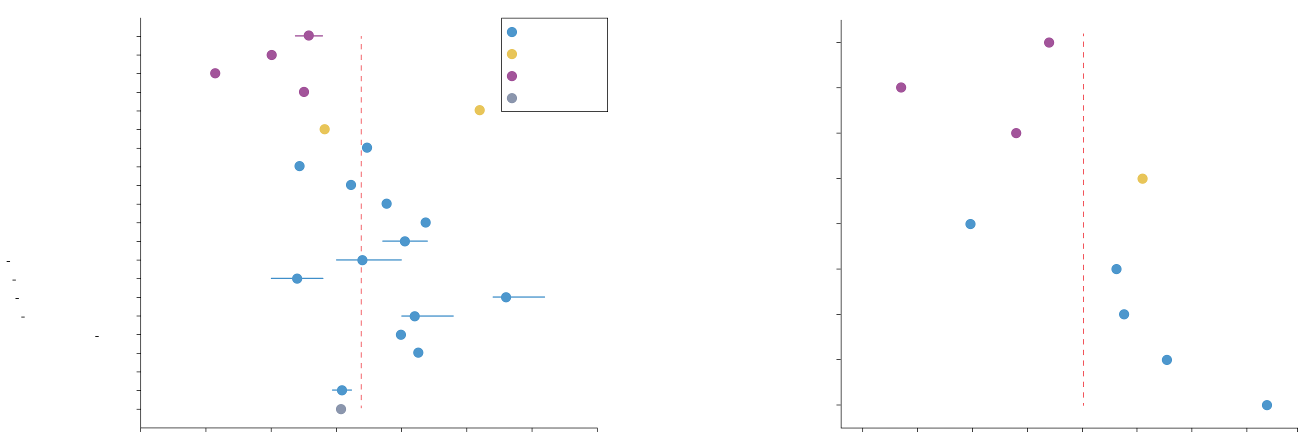

Fig. 2 | Global irrigation water withdrawals and consumption estimates. **a**, Literature estimates of global irrigation water withdrawals from different process-based models[4,46,50,54,55,64,202–208] (see Supplementary Table S2). When time-varying estimates are provided, the plotted value represents the latest year reported. If given, bars indicate the range in withdrawals, and red dashed line is the average across all estimates. Repeated models indicate multiple estimates made using the same hydrological model but different climate forcing. **b**, As in panel **a**, but estimates of global irrigation water consumption[4,50,54,55,203,204,208] (see Supplementary Table S2). The mean estimate of irrigation withdrawals across the models is consistent with reported estimates from the United Nations Food and Agriculture Organization (UN FAO); however, there is substantial variation across individual modelled estimates of both withdrawals and consumption. ESM, Earth system model; LPJmL, Lund–Potsdam–Jena managed land.

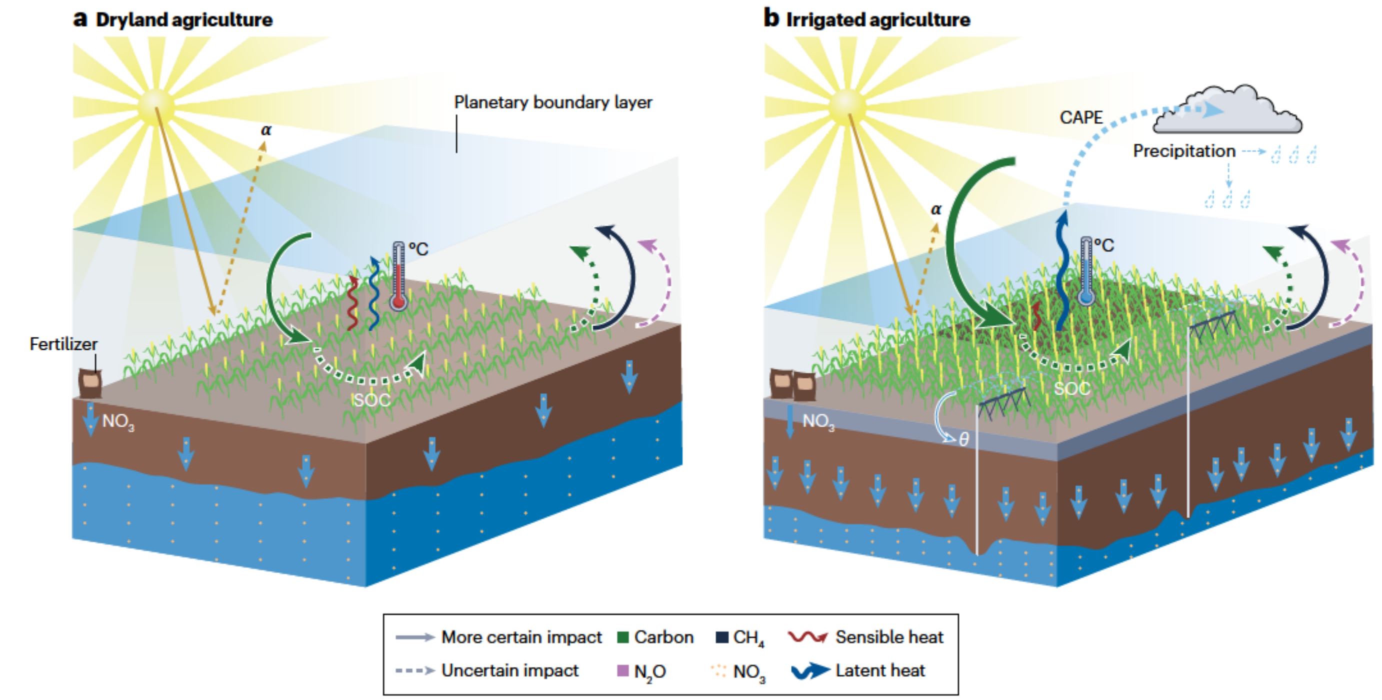

Fig. 3 | Irrigation–Earth system interactions. a,b, The key processes and mechanisms through which dryland agriculture (panel **a**) and irrigated agriculture (panel **b**) interact with the climate system and biogeochemical cycles. Dark green lines indicate the flows of carbon as CO_2 assimilated from the atmosphere from crop photosynthesis, carbon contained in decomposing biomass and soil organic carbon (SOC), and CO_2 emitted back to the atmosphere. *α*, albedo; CAPE, convective available potential energy; *θ*, soil water content. Dashed arrows indicate interactions with high uncertainty. Irrigation generally increases latent heat fluxes, while reducing sensible heat fluxes, and thus cools the surface during growing season daytime. Irrigation can also increase atmospheric water vapour, leading to changes in cloud cover or local and/or remote rainfall, while further mobilizing mineral nitrogen and increasing crop productivity and carbon assimilation.

partly driven by irrigation, can increase gross primary productivity, and therefore can increase the uptake of cropland carbon and nitrogen in agroecosystems. However, higher crop productivity might also incur higher respiration rates, with uncertain impacts on carbon storage. Irrigation could also increase methane and nitrous oxide emissions following intensification, especially in rice-based systems[81].

Furthermore, irrigation water fluxes that are not transpired by the crop can contribute to mineral nitrogen mobilization and leaching from agricultural soils. These nitrogen losses contribute to ground, surface and drinking water pollution, with nitrate levels above 10 ppm posing substantial risks to human health[82,83]. Irrigated regions such as the California Central Valley now have a legacy of agriculturally derived nitrogen in groundwater sources, such that this source of nitrogen fertilizer must be accounted for in efforts to improve the efficiency of crop nitrogen use (that is, the nitrogen uptake of the crop compared with the crop biomass or the crop yield compared with the amount of nitrogen applied) and reduce nutrient loading in the surrounding environment[84,85].

Impacts of irrigation on surface temperature

An increasing number of observations are finding that irrigation impacts regional temperatures and temperature trends[86], motivating investigation of the underlying mechanisms driving these temperature changes (Fig. 3) and how these effects vary with location and time. In general, irrigation-driven biophysical processes lead to daytime cooling. In the western IGB, this cooling is estimated at just under 3 °C during the summer and monsoon season[86], or around 1–2 °C during the winter and spring growing season from December to March, facilitated largely by groundwater irrigation[87]. In some growing regions in the United States, the amplitude of temperature reductions can be larger. Specifically, irrigation (Fig. 4a) and resultant increases in soil moisture (Fig. 4b) and evapotranspiration (Fig. 4c) contribute to June–August daytime cooling of >5 °C in the California Central Valley and Great Plains[13,86,88,89] (Fig. 4d). Groundwater irrigation expansion across Midwestern states, for example Wisconsin, might also reduce maximum temperatures by 0.2–1.1 °C and 0.2–1.8 °C compared with rainfed agriculture and forests, respectively[90]. However, irrigation does not appear to increase evapotranspiration and induce cooling over the Mississippi Embayment[86] (Fig. 4). This observation is partly caused by the weak land–atmosphere coupling in this humid region, where surface fluxes and resulting temperatures are not as sensitive to soil moisture variability as over the California Central Valley or Great Plains[86].

Observational evidence of irrigation-induced warming, particularly at night, and/or of minimum temperatures is also emerging. For example, in Wisconsin, irrigation-related soil moisture increases during and after the growing season (through soil moisture memory) also increased minimum temperatures, thereby shrinking the diurnal temperature range by ~3 °C throughout the year[90,91]. In the North China Plain, night-time warming trends of 0.009 °C $year^{-1}$ occurred during

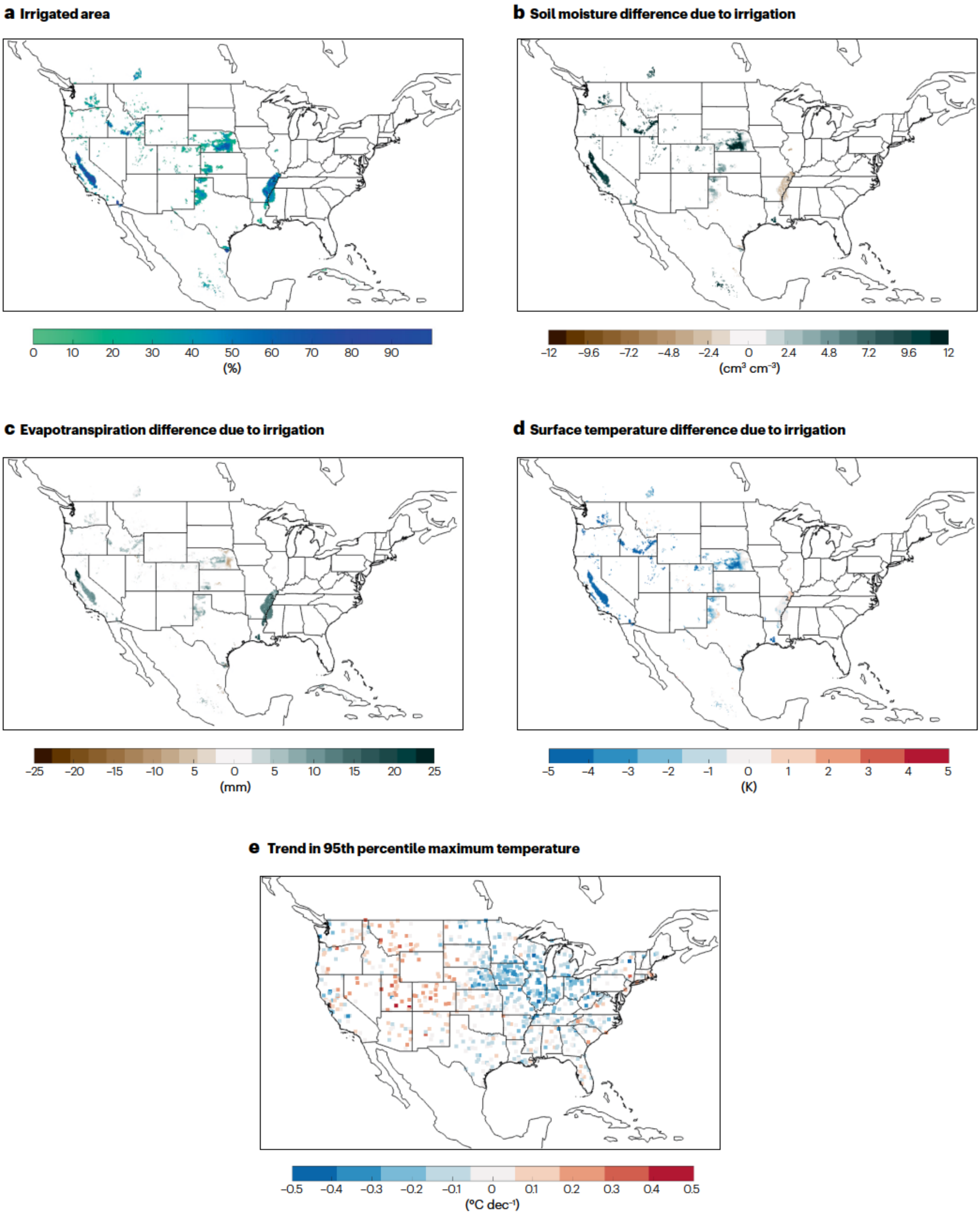
a Irrigated area
0 10 20 30 40 50 60 70 80 90
(%)
b Soil moisture difference due to irrigation
−12 −9.6 −7.2 −4.8 −2.4 0 2.4 4.8 7.2 9.6 12
(cm³ cm⁻³)
c Evapotranspiration difference due to irrigation
−25 −20 −15 −10 5 0 5 10 15 20 25
(mm)
d Surface temperature difference due to irrigation
−5 −4 −3 −2 −1 0 1 2 3 4 5
(K)
e Trend in 95th percentile maximum temperature
−0.5 −0.4 −0.3 −0.2 −0.1 0 0.1 0.2 0.3 0.4 0.5
(°C dec⁻¹)

Fig. 4 | Irrigation–climate impacts over North America. **a**, The difference in irrigation area between irrigated and co-located non-irrigated (<10% area irrigated) grids[86]. **b**, As in panel **a**, but the difference in June–August seasonal average surface soil moisture at depths to 5 mm during 2015–2017. **c**, As in panel **a**, but the difference in evapotranspiration during 2002–2017. **d**, As in panel **a**, but the difference in surface temperature during 2002–2017. **e**, The trend in 95th percentile of June–August maximum temperatures over 1910–2014 (ref. 79). See Supplementary Information for a detailed discussion and analysis of data product uncertainties. Irrigated grid cells mostly display an increase in soil moisture, enhanced evapotranspiration and a resultant cooling compared with co-located non-irrigated grid cells; in intensively cultivated agricultural areas of the Midwestern USA, irrigation also contributes to reductions in heat extremes.

1961–2004, coincident with irrigation expansion[69]. This warming exceeds the daytime cooling effect of irrigation, resulting in overall net warming of regional mean surface temperatures during the dry season.

Nevertheless, observations of the impacts of irrigation on temperature are complicated by historical agricultural intensification trends that have resulted in simultaneous physiological crop changes that impact crop water use and evapotranspiration[91]. Therefore, current understanding of irrigation–climate interactions is largely supplemented by the use of process-based models. Despite the key uncertainties in irrigation representation (Box 1), model experiments and diagnostics can improve understanding of which mechanisms (Fig. 3) dominate climate responses to irrigation.

Models confirm that irrigation has a cooling effect on daytime and growing season temperatures[75,86] across many regions. Irrigation could therefore be a warranted inclusion as a historical climate forcing in coupled ESM experiments and intercomparisons[14,92,93]. Models can also elucidate other, even competing, effects of irrigation. For example, some models indicate that in the IGB, irrigation reduces low cloud fractions and increases incident short-wave radiation resulting in enhanced net surface radiation[74,75]. Other model results show that irrigation increases daily night-time temperatures by increasing atmospheric water vapour and, thus, incident long-wave radiation[70]. In these experiments, increased mean daily temperatures were observed across key irrigated regions, such as the northwestern IGB and California Central Valley, if and when the magnitude of night-time warming exceeded that of daytime cooling[70]. Regional climate model simulations of urban and peri-urban areas have also demonstrated that planting drought-tolerant vegetation to reduce the need for irrigation could raise local temperatures in parts of Los Angeles[94].

The overall (daytime) cooling effects resulting from extensive irrigation can also attenuate hot extremes and their trends[64,86,95–100] (Fig. 4e). The attenuation of hot temperature extremes has been observed over extensively irrigated areas such as Nebraska[86] and across the IGB[87,101]. Reduced temperature extremes have also been simulated with climate model experiments[64,96]. Additionally, in the Mediterranean, irrigation attenuates both cold and hot extremes[64], although the effects might be more impactful for hot extremes because more irrigation water is generally added during the warmest and driest months.

In contrast to attenuating heat extremes, irrigation can also exacerbate moist heat stress both over directly irrigated areas[101,102] and in adjacent, densely populated areas downstream of irrigated lands[16]. Observational analyses from the central-northern US Great Plains reveal that the expansion of irrigation from 1990 to 2014 led to increased evapotranspiration and atmospheric moisture content during the growing season, dew point temperature and surface moist enthalpy[13,103,104]. Across many irrigated areas, irrigation increases wet-bulb temperatures[102] (that is, the lowest temperature to which an object can cool down through evaporative cooling). Observations show that the April–May Heat Index (a measure of stress resulting from combined heat and humidity) and wet-bulb temperatures over the IGB have increased steadily from 1979 to 2018, coinciding with the most extensively irrigated areas in South Asia[101,105]. Modelling results suggest that this moist heat stress increase over the IGB results from irrigation-induced increases in both regional specific and relative humidity, in addition to enhanced heat stress from climate change[101]. However, there is uncertainty in this result. Irrigation can also reduce monsoon moisture transport over the IGB[75], which would reduce wet-bulb temperatures[102] despite increasing incident short-wave radiation and elevating temperatures[102]. Furthermore, irrigation models constrained by the timing and amount of irrigation, which are derived from satellite vegetation indices, agricultural census data of irrigated areas and estimates of crop water requirements, suggest that irrigation might only have a small contribution to the rising moist heat extremes across the IGB, increasing relative humidity by only 2.5%[43].

Impacts of irrigation on precipitation

The impact of irrigation on precipitation is more varied than surface temperature and is strongly dependent on prevailing atmospheric circulation processes and hydroclimate regime[71]. Regional modelling suggests that springtime precipitation in the North China Plain can increase as a result of boundary layer moistening from evaporative fluxes over irrigated areas[106]. A similar mechanism also causes increases in June–September and annual precipitation over irrigated areas across the northwestern IGB in global climate model simulations[107], despite reduced monsoonal moisture transport. Furthermore, results from the Great Plains Irrigation Experiment (GRAINEX), which used surface and radiosonde data, show that increased latent heat flux owing to irrigation lowered the planetary boundary layer (that is, the tropospheric layer that is bound by the Earth's surface), the lifting condensation level and level of free convection, thereby altering mesoscale circulation[13,89].

However, irrigation's impact on precipitation might extend beyond in-situ moisture recycling and irrigated areas alone. In many regions, irrigation could also impact remote or downstream precipitation through interactions with thermodynamic processes, such as altering heat and moisture gradients to incite secondary circulation and/or interact with larger atmospheric circulation and atmospheric wave activity. For example, in the central-northern Great Plains, including Nebraska, observed increases in precipitation intensity downwind of irrigated areas during 1950–1980 might been caused by convective responses to altered mesoscale circulation induced by irrigation[108]. Between 1979 and 2015, precipitation over Nebraska decreased by 1 mm $year^{-1}$ (ref. 109) whereas downwind precipitation increased by an average of 0.5 mm $year^{-1}$. One explanation for this observation is that stable atmospheric conditions and subsidence over irrigated areas, resulting from changed surface energy partitioning, create moisture and energy gradients directed towards neighbouring unirrigated areas. These gradients can drive remote moisture convergence and uplift[15,108]. Feature tracking algorithms reveal other possible mechanisms that could be responsible for the remote impacts of irrigation on precipitation from the Great Plains to the eastern United States. Namely, irrigation could induce mid-level cyclonic circulation in the US Southeast that inhibits the eastward movement of mesoscale convective systems into the Mid-Atlantic region, but promotes locally produced mesoscale convection that increases precipitation[70]. Regardless of the mechanism, changes in convective precipitation caused by irrigation could redistribute regional streamflow and groundwater storage, thereby altering the regional water balance[110,111].

Similar processes could also be at work in the East African Sahel, across areas surrounding the Gezira irrigation scheme and over Saudi Arabia[112,113]. Both observations and model simulations over Saudi Arabia point to reduced precipitation directly over irrigated lands within the Gezira scheme, whereas precipitation increases east of the scheme[113]. Furthermore, both regional and global climate models have found that the presence of intensive irrigation along the IGB reduces meridional thermal gradients and alters the distribution and transport of moist static energy in ways that reduce South Asian summer monsoon circulation strength and regional rainfall over large parts of the subcontinent[75,114,115] and beyond[76].

Irrigation can also impact precipitation extremes, although these impacts are difficult to observe and simulations are subject to model uncertainties and limitations in simulating convection and the resulting precipitation. However, regional climate modelling experiments suggest that the propensity of irrigation to reduce rainfall and stabilize atmospheric conditions might have also exacerbated the high pressure anomalies of the La Niña-driven 2012 drought over the southern US Great Plains[15]. Enhanced atmospheric water vapour resulting from irrigation might also contribute to the increased precipitation intensity and extremes observed over northwestern South Asia[116].

Impacts of irrigation on biogeochemical cycling

Land models and ESMs are also being used to explore the impact of irrigation on biospheric carbon and nitrogen cycling. The use of irrigation and application of nitrogen fertilizer have risen together, or co-intensified, throughout the latter part of the twentieth century. This co-intensification, and resulting water-meditated losses of nitrogen, is one of the reasons that nitrogen use efficiency has fallen to 42–46% over the same period alongside a tenfold increase in the export of nitrogen to waterways as mobile nitrate[117,118]. In some semi-arid regions where irrigation increases without increasing nitrogen fertilizer application, there has been a threefold increase in nitrogen use efficiency[119] due to increased nitrogen uptake by plants[120]. However, increasing both irrigation and nitrogen fertilizer together also increases yields, up to 40% for wheat, for example[121].

Co-intensification of irrigation and fertilization can increase organic nitrogen stocks, nitrogen mineralization, infiltration, leaching to groundwater and export to surface waters – especially in semi-arid irrigation hot spots. Nitrogen loading to ground and surface waters in semi-arid regions is often decoupled in time from the growing season, as water fluxes larger than those associated with growing season irrigation events are required to move nitrogen (as nitrate or organic nitrogen) from soils to ground and surface waters. For this reason, measured nitrate fluxes to surface or groundwaters are higher than would be estimated based on the previous growing season alone because these fluxes include all previously stored excess or 'legacy' nitrogen. For example in the Flumen River watershed in Spain, nitrate infiltration rates ranged from 100 to 250 kg N ha^{-1} $year^{-1}$ on irrigated lands, which was less than the 600–1,400 N kg ha^{-1} $year^{-1}$ of nitrate lost from the same lands to the river following the growing season[122]. This difference is because precipitation occurring outside the growing season mobilized legacy soil nitrogen to drive the higher lateral flows to adjacent surface waters, leading to a measured discharge rate of 600,000 kg N $year^{-1}$ at the mouth of the Flumen River[122].

Irrigation water sourced from groundwater and surface water also contains nitrogen that is not systematically factored into fertilizer application amounts, which can contribute to the overapplication of nitrogen fertilizer and increases in soil nitrogen mobilization and leaching. Irrigated regions such as California Central Valley now have a legacy of agriculturally derived nitrogen in groundwater, which must be accounted for to improve nitrogen efficiencies and reduce loading[84,85]. Nearly 88% of groundwater nitrate originates from irrigated agricultural lands in California[123,124]. Of the 331–333 Gg N $year^{-1}$ of nitrate that moves into California's groundwater, 33 Gg N $year^{-1}$ is extracted as irrigation and reapplied with additional nitrogen fertilizer[124]. The Irrigated Lands Regulatory Programme[125] is an example of a new policy incentivizing growers to account for this nitrogen flux in their fertilizer applications.

Irrigation can also impact terrestrial carbon storage. Higher crop growth resulting partly from irrigation could enhance carbon sequestration at the watershed[120] scale. In water-limited regions, irrigation can facilitate carbon sequestration by supporting microbial biomass through increased soil moisture and nitrogen[120,126,127]. For example, in the Upper Columbia-Priest Rapids, an important watershed in Washington state, irrigation decreased the net ecosystem exchange of carbon by 76 and 140 g C m^{-2} $year^{-1}$ for soybean and maize, respectively[120]. Similarly, in the Heihe River Basin, transitioning from rainfed to irrigated agriculture shifted the net ecosystem exchange from 6 g C m^{-2} $year^{-1}$ to −229 g C m^{-2} $year^{-1}$ (ref. 17).

However, these soil carbon gains might not compensate for the increased emissions of greenhouse gases (such as CO_2, CH_4, N_2O), particularly in rice-based systems. Alternate wetting and drying irrigation management, which is being increasingly promoted in rice cropping systems[128], can increase autotrophic nitrification, heterotrophic denitrification and methanogenesis from anoxic portions of soil aggregates[129]. Continuous flood irrigation of rice paddies releases methane at a rate of 35–2,328 kg ha^{-1} $year^{-1}$ (refs. 130,131), whereas intermittent flood irrigation releases methane at −156 to 706 kg ha^{-1} $year^{-1}$ with the transition to intermittent flooding or alternate wetting and drying generally decreasing methane emissions[132,133]. Similarly, the emission of nitrous oxide to the atmosphere can range from −1 to 15 kg ha^{-1} $year^{-1}$ (refs. 134,135) in rice paddy systems, and transitions from continuous to intermittent flood irrigation produce unclear results[129,134]. Moreover, conversions from reductive flood irrigation conditions to more efficient micro-irrigation methods can decrease soil carbon pools[129,136].

Furthermore, some irrigation practices (such as flood irrigation) might also induce soil erosion, redistributing sediment and soil carbon on land and/or to adjacent surface waters[137]. One model estimate suggests that conversions from rainfed to irrigated agriculture in India and China could result in a 10% increase in erosion, although many uncertainties remain[132]. Alternative irrigation systems, such as broad bed and furrow approaches, could reduce soil erosion and carbon losses in semi-arid growing regions such as India[133], partly owing to the differences in slope and infiltration rates of water into soil. However, conversions to more efficient irrigation systems could also partly facilitate irrigation expansion in these regions into areas with little ground cover and increased slopes, thus increasing soil erosion and carbon losses[138].

Future climate–irrigation interactions

Future climate changes have the potential to alter the way in which irrigation interacts with Earth systems. In tandem, irrigation demand is expected to increase owing to both climate change and ongoing sectoral development trends[5,22], adding to the existing complex interactions. Current research on the impacts of future climate and socioeconomic trends on irrigation–Earth system interactions as well as potential irrigation scenarios is reviewed below.

The effect of anthropogenic warming on climate–irrigation interactions

Future changes in atmospheric CO_2 concentration, temperature and precipitation will affect irrigation demand, thereby inciting additional interactions with the Earth system. The primary biophysical driver of irrigation demand is potential crop evapotranspiration. Under constant relative humidity, the atmospheric demand for evapotranspiration is expected to increase by approximately 6.8% per 1 °C of warming (following the Clausius–Clapeyron relation)[139]. Increased atmospheric CO_2 concentrations (alongside rising temperatures) can facilitate stomatal closure and enhance photosynthetic efficiency in C_3 crops, potentially decreasing water demand by reducing leaf-level transpiration and improving water use efficiency[62,140–142]. Model intercomparison of crop responses to enhanced atmospheric CO_2 concentrations suggests possible mean increases in crop water productivity of ~10–27% (ref. 62).

However, the degree to which CO_2-driven improvements in water use efficiencies might be offset by simultaneous increases in evaporative demand and other plant physiological changes remains an active area of inquiry[143–145]. Crop yield could be largely constrained by the rise in vapour pressure deficit under current cropping conditions, potentially requiring substantial additional irrigation under future climates[146]. Rising temperature trends, particularly since the 1990s, are contributing to increased vapour pressure deficit over land and might be attenuating global greening trends driven partly by CO_2 fertilization[147]. The net impact of these interacting effects on drought frequency and severity is also a topic of ongoing debate[148].

Future climate projections indicate that global terrestrial precipitation might increase by 1–3% per 1 °C of warming by 2100 (ref. 149), but with large regional variations including increased precipitation in the tropics and mid and high latitudes, and decreased precipitation in the subtropics[149]. It is possible that increased precipitation could decrease irrigation demand in some areas; however, the changes in various components of the land water balance[150] under higher temperatures and evapotranspiration make it difficult to perform a simple assessment. Further, changes to temporal variability and precipitation intensity introduce additional uncertainties to predictions of future irrigation demand and water availability.

Soil moisture is a key variable that influences irrigation water demand and agricultural drought (that is, the local soil, surface and atmospheric moisture conditions that inhibit meeting crop water demand and result in adverse crop responses). However, hydrological drought, in which surface and sub-surface water supplies are depleted owing to a lack of precipitation, and reductions in snowmelt and glacier-fed waters where relevant, will influence surface water and groundwater stores available for irrigation[151,152]. The risk of climate change-induced reductions to long-term irrigation water resources might be particularly acute in areas that are (increasingly) dependent on snowmelt and glacier outflows. For example, seasonal snowmelt provides an important fraction of the required soil moisture across growing regions in Germany and the United Kingdom, and snowmelt risks to irrigated agricultural supplies could increase from near zero to 16% and 10% in Germany and the United Kingdom, respectively, under an increase of global temperatures of 2 °C (ref. 152). Furthermore, agriculture along the Indus River might increasingly rely on meltwater as climate change continues, particularly during planting periods in the pre-monsoon season in May and June[151].

The extent to which irrigation might serve future climate adaptation, by attenuating rising temperature trends over existing irrigated areas[79] potentially through higher irrigation rates and/or increasing irrigation supplies and access (owing to expanded infrastructure) in previously rainfed areas to ameliorate the effects of heightened climate variability, is a subject of much interest[14,93]. Global climate model experiments extending model estimations of the present-day extent and application rates of irrigation to 2100 suggest reduced rates of warming and drying across many irrigated areas, including Mexico, the Mediterranean, the western IGB, and northern and eastern China[153]. However, more rigorous evaluations that account for key model uncertainties and sensitivities (Box 1), and the use of multi-model approaches, can help better explore this question[93].

Furthermore, irrigation modelling must also explicitly consider the impacts of extreme events and the feasibility and potential consequences of perpetually sustaining current irrigation rates, including accounting for climate change-driven limitations on water resources[150], irrigation contributions to moist heat stress and unsustainable water use[101,153]. Continued trends in irrigation expansion, such as increased water withdrawals and irrigation infrastructure, might reduce environmental flows, impacting downstream water availability and ecosystems[154]. Increased water withdrawals, both from surface and groundwater stores, could further exacerbate climate-driven reductions in water availability[155], particularly under drought[156].

The impact of changing water demands and climate on irrigation

Global demand for irrigation is expected to increase alongside climate change and sectoral development trends[5], putting pressure on water supplies[17]. In tandem, climate change-induced changes to water storage[150] and hydrological cycling will further change the availability of water for irrigation[22,157]. Coupled model frameworks provide opportunities to explore how scenarios of future irrigation water demand could be constrained by both climate change impacts on water availability as well as co-evolving socioeconomic development, including food and energy transitions[158]. However, rigorous multi-model assessments of future irrigation water demand with biophysical constraints are still lacking.

Preliminary process-based estimates point to lower overall future irrigation water requirements under unabated climate change scenarios[142] due to the interacting effects between shorter growing seasons (caused by hastened crop phenological development) and CO_2 effects on the efficiency of water use by crops, reducing water requirements in the absence of improved (that is, slower-maturing) cultivars. However, atmospheric water demand could increase across many growing regions leading to higher evapotranspiration. Future irrigation, including scheduling, techniques and amounts, will therefore depend on the interactions of simultaneous changes in both climate and human water pressures, which also extend beyond pure biophysical considerations (Box 1). The water use outcomes of these coupled natural–human processes could modulate the various impacts of irrigation on the climate and environment; therefore, it is worthwhile to integrate these processes in ESMs in some capacity[7,158]. For example, nested modelling approaches[159] have been developed to integrate future climate projections with hydrological modelling, accounting for water infrastructure, resources and human decision-making with respect to irrigation water withdrawals. When tested in southeastern Australia, fossil fuel-driven climate scenarios coupled with high irrigation demand were shown to lead to water scarcity that is comparable with historically significant regional droughts[22]. Although these modelling approaches make it possible to explore future irrigation scenarios, it is crucial that irrigation modelling communities develop and employ a range of approaches to bracketing current model uncertainties and limitations (Box 1) to facilitate a useful integration of these coupled processes.

At the global scale, annual freshwater demand for irrigation is projected to stay at least at current levels, with ~545 km^3 of irrigation water being sourced from groundwater[1,51], which is likely to increase as the irrigated area expands[157]. It is also possible that, owing to systemic uncertainties in population and development trends as well as in the assumptions of water availability, demand and use, model-based predictions underestimate the global irrigated area. One such model suggests that the global irrigated area will reach 240–450 Mha by 2050 (ref. 157). Estimates of future irrigation demand based on population size rather than density that account for uncertainties in both irrigated area data aggregation and model parameters project ranges spanning 300–800 Mha (ref. 63). Even in some water-limited areas, across semi-arid Africa, total blue water consumption for irrigation (that is, water originating from surface and groundwater stores) is expected to increase by 20–130 Mha by 2050 according to some estimates[157]. However, intensifying irrigation application rates could be more limited in practice owing to the feasibility of infrastructural development, maintenance and region-specific increases in irrigation costs as water resources become scarcer[160,161].

To capture some of the uncertainty across collective human decision-making on climate change mitigation and global development, the climate community has developed and leveraged the shared socioeconomic pathways (SSPs)[162]. The SSPs constitute future scenarios by which the climate community can evaluate a range of climate impacts, and adaptation and mitigation options, ranging from high-ambition greenhouse gas mitigation to strongly fossil fuel-oriented scenarios with varying levels of climate justice and equity. Land use trajectories that are consistent with these SSP scenarios are important because they serve as inputs to ESMs and sectoral models that contributed to the Sixth Intergovernmental Panel on Climate Change (IPCC) Assessment Report[163,164]. These trajectories were developed by the Land Use Harmonization Project 2 (ref. 165), and were designed to continuously connect historical land use and management reconstructions, based on the History of the Global Environment database, with the various SSP future projections.

These land use trajectories include quarter-degree global gridded maps of the area equipped for irrigation as it varies through time from 850 to 2100 (Fig. 5) that broadly capture historical irrigation expansion and future changes depending on the extent and intensification of agricultural development[165]. Scenarios of equitable, enhanced global development still include agricultural intensification, and thus expanded irrigation (Fig. 5). Even decarbonization scenarios include increased biomass and bioenergy crop production, which might further increase irrigation water demand[166,167]. This demand could potentially induce local water stress in otherwise ambitious climate mitigation pathways. However, the production of crop bioenergy could be substantially limited by restricting water use to sustainable abstractions[168] and, importantly, by the availability of non-renewable or limited water resources[161,169].

Considerations for irrigation sustainability

The future availability of freshwater will pose a major constraint on future irrigation expansion and development, as will the sustainability of existing irrigated agricultural systems, particularly those that are heavily reliant on groundwater such as in the IGB[170,171] or Great Plains[172,173]. Sensitivity estimates from global gridded crop modelling experiments suggest that reductions in freshwater availability and/or access could cause 20–60 million irrigated hectares to revert to rainfed agriculture[174], which could have a profound impact on entire cropping systems. Although these potential changes have implications for future water supplies, these estimates do not directly incorporate irrigation–Earth system interactions and feedbacks or possible adaptive responses. What constitutes 'sustainable' irrigation can be debated, but there is broad agreement across the available literature that, at a minimum, sustainable water consumption should stay within local renewable water (surface and ground) availability and account for the freshwater flows and reservoirs needed to sustain natural ecosystems[54,175].

The extent to which freshwater limitation will impact irrigation will depend on the availability of adequate environmental flows[58], which have already been substantially reduced by current irrigation water use[54], and the development of conservation-oriented water management approaches. Global crop model experiments have been used to evaluate ideal scenarios of ambitious changes to current irrigation practices, including the widespread adoption of sprinkler or drip systems, rainwater harvesting and managed reductions in soil evaporation. Such measures could restore river flows, which are needed to sustain key aquatic ecosystem services, while reducing consumptive losses and mitigating possible shortfalls in crop production[54]. Crop model sensitivity experiments that enhance crop water (irrigation) productivity also save water and close yield gaps in water-limited domains, thereby boosting global calorie production by more than 26%, depending on the ambition of the water conservation measures deployed[176] (Fig. 6a). Although there are still challenges for modelling present-day irrigation efficiencies, experiments such as these provide a scenario and/or limits approach to investigating sustainability in irrigated agriculture.

Work to explore the potential for improved irrigation management options could further be integrated with coupled ESMs to investigate the implications for feedbacks and interactions. For example, idealized irrigation–climate experiments across the IGB indicate that prescribed reductions in irrigation applications, potentially achieved through stronger water use regulations, can minimize irrigation-induced disruptions in regional precipitation[116]. Changes in management, however, occur both at the field level and also through institutional and public works measures, for example dams and reservoirs. Yet representations of the latter are largely still lacking in model frameworks[121]. Incorporating these elements into models could help better bracket uncertainties and establish potentials for food production and water savings. For example, global experiments using a combined crop–water model have identified agricultural regions that could benefit from improved irrigation management strategies, including 'soft measures' that farmers can take to conserve water at the field level as well as implicit representations of large, centralized, capital-intensive irrigation projects and water storage infrastructure (for example, large reservoirs)[175] (Fig. 6b).

Model results suggest that these infrastructure changes could sustainably feed 1.4 billion more people globally while retaining environmental flows[175]; however, these models did not account for socioeconomic and political conditions that could impact the implementation of these measures.

Although improvements in irrigation efficiency at the field level are a crucial step for conserving water, such improvements might not always lead to water conservation. For example, controlled case studies to test the water-saving potential of drip irrigation in southern India showed that gains in efficiency might be offset by changes and expansion of the cropping system and farmers' crop choices[177]. More broadly, it has been argued that on-farm increases in irrigation efficiency should be implemented alongside enhanced methods of water use measurement and accounting as well as regulatory measures aimed at assessing the best use of water considering the changing environmental conditions and conserving water resources overall[178,179]. Although these are needed developments in irrigation research, it is also important to acknowledge the complexity of irrigation decision-making, which occurs on different spatial and temporal scales and with a wide variety of knowledge frameworks[179].

Ultimately, the rules in place for use, sharing, maintenance and conflict resolution along a watercourse shape which users receive enough water, what crops are planted or whether anything is planted at all[180,181]. At larger scales, the capacity to measure water flows and assign rights to water access shapes the potential for water trading along and across irrigation channels[182,183]. Furthermore, increasing demand from non-agricultural sectors can challenge the assumed large water allocation assigned to agriculture and engender more inter-sectoral competition as resources flow to the application with the highest economic value[184]. For example, increased irrigation demand, partly to support the growth of non-native vegetation, accounts for 40–70% of water consumption in arid and semi-arid cities, depending on climate, pricing and sociodemographic factors[185].

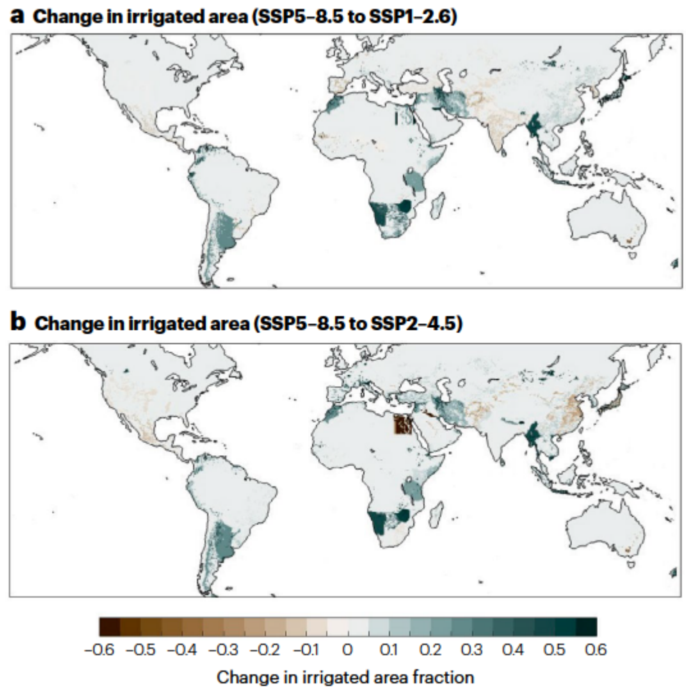

Fig. 5 | Projected changes in irrigated area. a, The difference between predicted irrigated area fraction[209] by 2100 from SSP5–8.5 (fossil fuel-driven development scenario) and SSP1–2.6 (ambitious climate change mitigation scenario). **b**, As in panel **a**, but the difference between SSP5–8.5 and SSP2–4.5 (an intermediate 'middle of the road' climate change mitigation pathway). Irrigated areas expand most in the fossil fuel-driven scenario across both Africa and South America, although in other parts of the world, such as southern North America and South Asia (in the case of SSP1–2.6), the higher-ambition mitigation scenarios show more irrigation expansion, related in part to changes in cropping patterns and expanding irrigation infrastructure. SSP, shared socioeconomic pathway.

Summary and future perspectives

Irrigation research has expanded substantially since the early 2000s, resulting in increased amounts of regional data, updates to global irrigated area maps and the implementation of irrigation in process-based sectoral models (for example, models of agriculture and water) and coupled ESMs. Collectively, these data and model analyses reveal that irrigation has important interactions with Earth system components and processes, which must be further explored and bracketed in the context of model uncertainties (Box 1). In particular, irrigation impacts climate processes by altering surface energy and moisture balances, exchanges with the atmosphere and biogeochemical cycling. These irrigation–Earth system interactions have implications for a range of ecosystem services, such as crop production, carbon sequestration on agricultural lands, water availability and even human health[83].

Nevertheless, research inquiries into the impacts of irrigation on the Earth system are still nascent. Continuing research requires improvements across data products, tools and approaches, as well as a considered and deliberate approach to understanding their myriad uncertainties[157,186] (Box 1). Considerations of these uncertainties should extend beyond enhancing model accuracy or realism to include critical discussions on how models are developed and by whom, what biases or assumptions are inherent to this process and their ultimate adequacy for problem solving and transparency to potential end users[187]. To achieve this goal, coordinated, interdisciplinary engagement will be crucial to identify problematic assumptions, sources of uncertainty, research limitations and needs, and ultimately define and address the emerging questions on the impacts of irrigation on the climate, ecosystems and public health. Furthermore, interdisciplinary engagement combined with systematic uncertainty assessment and sensitivity testing are also crucial for the results of irrigation modelling to be relevant for potential policy applications: current limitations could preclude responsible policy recommendations based on model outputs[186].

We therefore recommend that efforts to better locate and quantify uncertainty across data and modelling efforts (Box 1) should be a priority for near-future, cross-disciplinary irrigation research. An important research task is to engage the relevant biophysical modelling and data communities to better assess common and unique uncertainties, strengths and limitations in simulating irrigation water availability and demand in the context of myriad irrigation–climate interactions[188]. Some existing frameworks offer best practices to systematically evaluate model uncertainties, conduct sensitivity tests and inform peer-review guidelines for structural model evaluation[188]. These practices include engaging in widely practised Monte Carlo approaches to assess parametric uncertainties and also moving beyond one-at-a-time sensitivity testing to more comprehensively investigate interactions between multiple, simultaneously changing parameters.

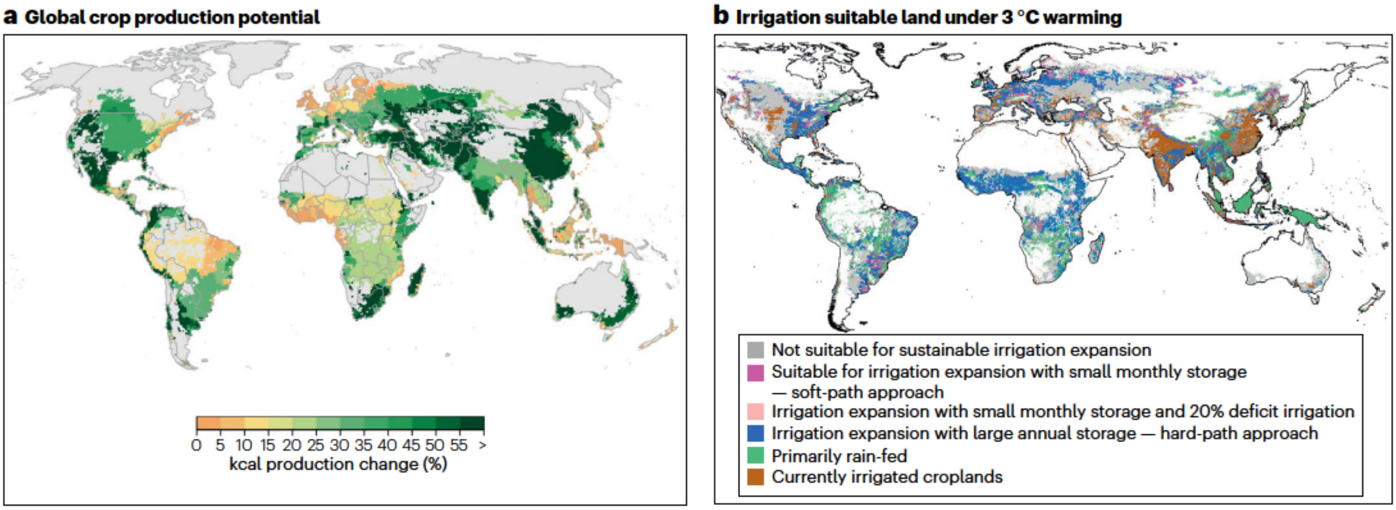

Fig. 6 | Potential for sustainable irrigation. a, The potential increase in global crop production (and therefore increase in calories produced) that could be achieved through rigorous implementation of improved on-field crop water management. This scenario includes the use of practices such as irrigation transitions, mulching, conservation tillage and irrigation expansion based on freed-up water withdrawals. Grey areas denote unirrigated and/or uncultivated landscapes. **b**, Global distribution of areas that could become suitable for irrigation expansion under 3 °C warming based on Earth system model future projections. Colours indicate the type of expansion that could be achieved. Irrigated lands could be expanded in the future and under changing climate conditions using various approaches, although real-world social, economic and political conditions could introduce constraints on realized expansion. Part **a** is reprinted from ref. 176, CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/). Part **b** is reprinted with permission from ref. 175, PNAS.

Assessing parametric uncertainty, which will increase as process-based models incorporate more realism and complexity[189,190], is particularly important[189,190] and new approaches to do so are emerging. For example, improvements in computational capacities increasingly allow for 'perturbed parameter ensembles' that combine parameter sensitivity simulations that use process-based models with evaluation metrics to determine key parameter subsets[189]. Importantly, this process requires that modellers identify and document all model parameters, opening opportunities to interrogate these values and their plausible ranges. Identified parameters can be calibrated to observations using machine learning approaches, where possible, and could also be used as parameters in efficient offline emulation[189]. The development of evaluation metrics for irrigation modelling would benefit from structured cross-disciplinary discussions for example, including those involved in research and practice. In addition, assessments of irrigation models' sensitivity to inputs, such as irrigated area maps and cropping system representation, are also critical and would benefit from systematic protocols in coordinated research initiatives (for example, model intercomparisons) on irrigation–Earth system interactions. To apply these models to decision-making, using expert judgement to develop constraints and/or co-developing models with irrigation decision-makers can help establish understanding and build confidence around sectoral impact modelling.

The similarity between models, which arises from common development history, user or institutional model attachment and rapidly rising process complexity (among other things), can reduce understanding of models and/or their adequacy for certain questions (Box 1). One response to these concerns could entail employing modular model frameworks, whereby key model processes are represented in various ways that can be efficiently interchanged and intercompared[190]. Therefore, modularity could enable a wide set of collaborators to easily contribute to model development and utilities, thereby expanding the types of research questions to which models are applied[191]. Additionally, modularity enables experiments to vary over the complexity of different process representations as well as development epistemologies. This capacity allows the broader irrigation research community to better evaluate development choices, model sensitivity and process additivity when tackling key research questions[190].

Alongside modularity, it is also worth considering how high-resolution modelling can be used to resolve landscape heterogeneity (including water management structures), represent local hydrological processes, locate sources of uncertainty and achieve targeted Earth system sensitivity testing in irrigation modelling[192,193]. Prior work has demonstrated that accounting for subgrid-scale heterogeneity in ESMs of land–atmosphere fluxes, surface energy balance[194] and even dams and reservoirs[12,195] substantially alters key climate variables, which influences the impacts of irrigation on the climate and environment at the landscape scale.

Furthermore, advanced uncertainty evaluation and sensitivity testing frameworks could also be usefully integrated into new protocols for model intercomparisons of irrigation–Earth system interactions. For example, the experimental protocols of the IRRigation impacts Model Intercomparison Project (IRRMIP) coordinate the simulation of historical, time-varying irrigation impacts on the climate system. With multiple ESMs participating, the anticipated results will help robustly identify the effects of historical irrigation expansion on the near-surface climate, the carbon cycle and terrestrial hydrology. IRRMIP, and other potential model intercomparison projects, provide large data sets that enable robust statistical results to be obtained particularly for climate extremes and compound extremes, such as those impacting heat stress. Irrigation intercomparison protocols also exist for the Global Gridded Crop Modelling Intercomparison (GGCMI) project, which was developed for a subset of hybrid crop–hydrological models. These protocols can generate multi-model estimates of surface water availability for irrigation that are then used as inputs for the remaining GGCMI crop models that cannot represent river routing. The Land Use Model Intercomparison Project (LUMIP)[92], an endorsed satellite model intercomparison project in the Sixth Coupled Model Intercomparison Project, also specified irrigation-specific protocols for land surface model experiments.

Combined with systematic uncertainty and sensitivity assessment, process-based model intercomparison projects that include irrigation, alongside empirical modelling of irrigation impacts on the Earth system, can also help identify irrigation impacts that are robust and important for attributing observations of regional climate change[196,197]. Current climate attribution work depends on model simulations with combined and individual anthropogenic forcings, such as greenhouse gasses, aerosols and changes in land use or cover. The latter, however, does not often include irrigation, which could partly contribute to inconsistencies between simulated and observed changes[65] and limit understanding of regional climate change[93].

Lastly, beyond modelling, expanded regional field campaigns such as GRAINEX[13] and Land Surface Interactions with the Atmosphere over the Iberian Semi-Arid Environment (LIAISE)[198] across global irrigated areas will help the wider community better understand variation in irrigation–climate interactions. Long-term networked monitoring of irrigation–climate interactions across irrigated areas, in the vein of the USDA long-term agricultural research sites, would also be beneficial to observational capacities and inform the modelling community. Satellite-based data products such as ECOSTRESS (ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station)[199], NISAR (NASA-ISRO Synthetic Aperture Radar), ROSE-L (Radar Observing System for Europe L-band), the Copernicus LSTM (Land Surface Temperature Monitoring) mission and the European Space Agency's Irrigation+ provide opportunities to further improve and refine methods for irrigation data retrieval at high spatio-temporal resolution. These efforts will advance irrigation mapping, seasonal irrigation detection and even the quantification of applied irrigation water amounts from space. Furthermore, coordinated biophysical irrigation research should also integrate community-developed methods to evaluate the impacts of irrigation on land–atmosphere coupling and soil moisture[88,200]. Ultimately, the outcomes produced by cross-disciplinary irrigation research efforts will help better match evolving model capacities with appropriate research questions, particularly those associated with understanding the current and future impacts of irrigation on the Earth system.

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