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Scenarios of sustainable irrigation expansion in the 21st century

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Abstract | Irrigation expansion onto rainfed croplands is an important part of the portfolio of agricultural measures, contributing to a more resilient crop production while enhancing agricultural yields. Existing global assessments of irrigation illustrate the biophysical potential, but generally do not account for socioeconomic and environmental constraints to irrigation deployment. Here we provide scenarios of regionalized sustainable irrigation expansion linked to socioeconomic projections from the Shared Socioeconomic Pathways framework, while accounting for biophysical irrigation limits. Under a Sustainability scenario, we find that sustainable irrigation could feed 2 billion people globally by 2100. With an additional 90 million people, sub-Saharan Africa is the region with the highest percentage increase in people fed via sustainable irrigation deployment. However, even under the most optimistic scenarios only half of the theoretically possible global biophysical irrigation potential would be utilized after accounting for socioeconomic constraints. Our results highlight the need for appropriate representation of socioeconomic factors in scenarios of future irrigation deployment.

Introduction | More than 800 million people are currently chronically undernourished¹. To meet the global increase in food demand, which is mainly driven by population and income growth, projections suggest that current global crop production needs to at least double by 2050². Most agriculture is currently rain-fed, but climate change is expected to change rainfall patterns and further exacerbate existing water- and heat-stress⁴. Irrigation expansion, despite its documented caveats^{3,4}, plays an essential part in the portfolio of response options by offering the possibility to increase crop yields via the maintenance of reliable water supply, while potentially also alleviating biogeophysical effects on temperature extremes⁵. Irrigation will also have an important role in the sustainable intensification of agriculture, an effort to halt agricultural expansion by increasing crop yields over underperforming cultivated lands⁶. However, half of global irrigation practices are unsustainable because they are depleting freshwater stocks and impairing environmental flows⁷ (Box 1). Recent global studies assessed biophysical constraints to sustainable irrigation and found that global rain-fed croplands hold significant potential for sustainable irrigation expansion because water will likely be available to suffice irrigation water demand without depleting environmental flows and freshwater stocks^{2,8}. These studies find that around 2.4 billion people are currently being fed via irrigation – half of it unsustainably⁸. If the biophysical potential for sustainable irrigation was to be exhausted, a total of 4 billion people could be fed via the calories that could potentially be produced⁸. The analyses focused on hydrological limits to irrigation expansion onto rain-fed croplands, without accounting for other socioeconomic factors that might also influence irrigation expansion potentials. Yet, in over 25% of global rain-fed croplands, irrigation is limited by institutional and economic capacity instead of hydrologic constraints, a condition known as agricultural economic water scarcity⁵. In fact, social, political, and economic factors will ultimately influence future irrigation development⁹. Therefore, there is a pressing need to

couple biophysical assessments of irrigation expansion potential with socioeconomic projections to identify future target regions for sustainable intensification of agriculture through irrigation expansion.

In this study we assess the irrigation crop yield gap – the difference between the actual crop yield and the maximum potential yield that could be achieved by deploying sustainable irrigation⁶. To study how the current deployment of sustainable irrigation varies across countries and over time, we introduce the Sustainable Irrigation Deployment Index (SIDI), which indicates how much of its domestic sustainable irrigation potential a country is currently using in comparison to what could be possible under maximum sustainable irrigation. We assume that the extent to which the yield gap can be closed by deploying sustainable irrigation depends on the societal ability to do so (we refer to this property as adaptive capacity), which in turn is a product of various socioeconomic resources such as governance¹⁰. By determining which socioeconomic factors enable or hinder the implementation of sustainable irrigation in the agricultural sector, we are able to holistically project sustainable irrigation deployment alongside the Shared Socioeconomic Pathways (SSPs)¹¹ throughout the 21st century (Box 1). It is important to understand the factors that enable or hinder the deployment of sustainable irrigation, as well as the temporal dimension of those factors. Thus far, these socioeconomic factors remain overlooked in assessments of potential future irrigation deployment, including climate impact models, which tend to assume optimal or maximum possible irrigation and thereby overstate its benefits¹².

The Sustainable Irrigation Deployment Index | The SIDI is defined as the ratio between the current sustainably irrigated calorie production and the maximum potential yield that could be attained at yield gap closure (YGC) by deploying sustainable irrigation (see Fig. 1 and Methods section for more detail). Typically, maximum potential yield is defined as the yield of a crop cultivar when it is grown in an environment with non-limiting water and nutrient supplies, sufficient light and no pests or diseases¹³. While progress in technology has allowed for large quantities of nitrogen fertilizers to be produced, water still remains a critical input limiting food production⁵. Therefore, we here consider the yield gap attributable to a crop water deficit but for the sake of simplicity, we use yield gap closure (YGC) to refer to a scenario where no water limitation is prevalent. The yield gap is considered closed when there is no difference between potential sustainable irrigation and the actual sustainable irrigation of countries⁸. We build on previous estimates of the sustainable irrigation potential under current conditions and a scenario of YGC⁸. The SIDI by design informs on the potential for sustainable irrigation deployment, which should not be interpreted as a measure of the share of sustainable versus unsustainable irrigation in a country at a given point in time (see Fig. S2).

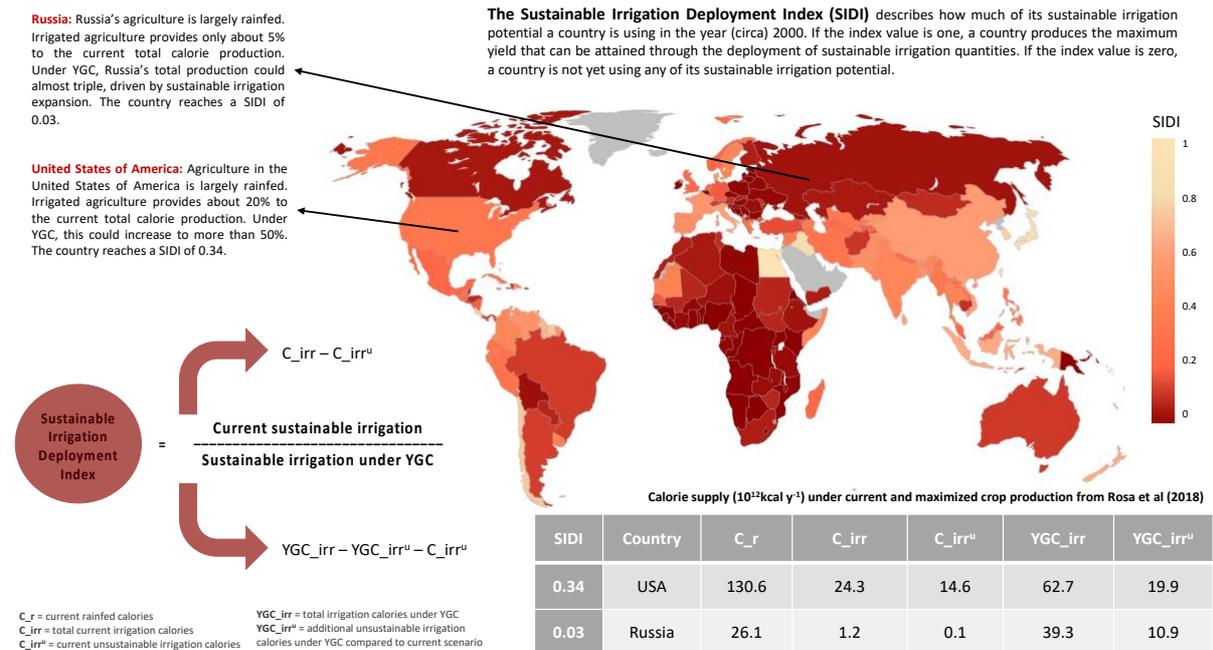
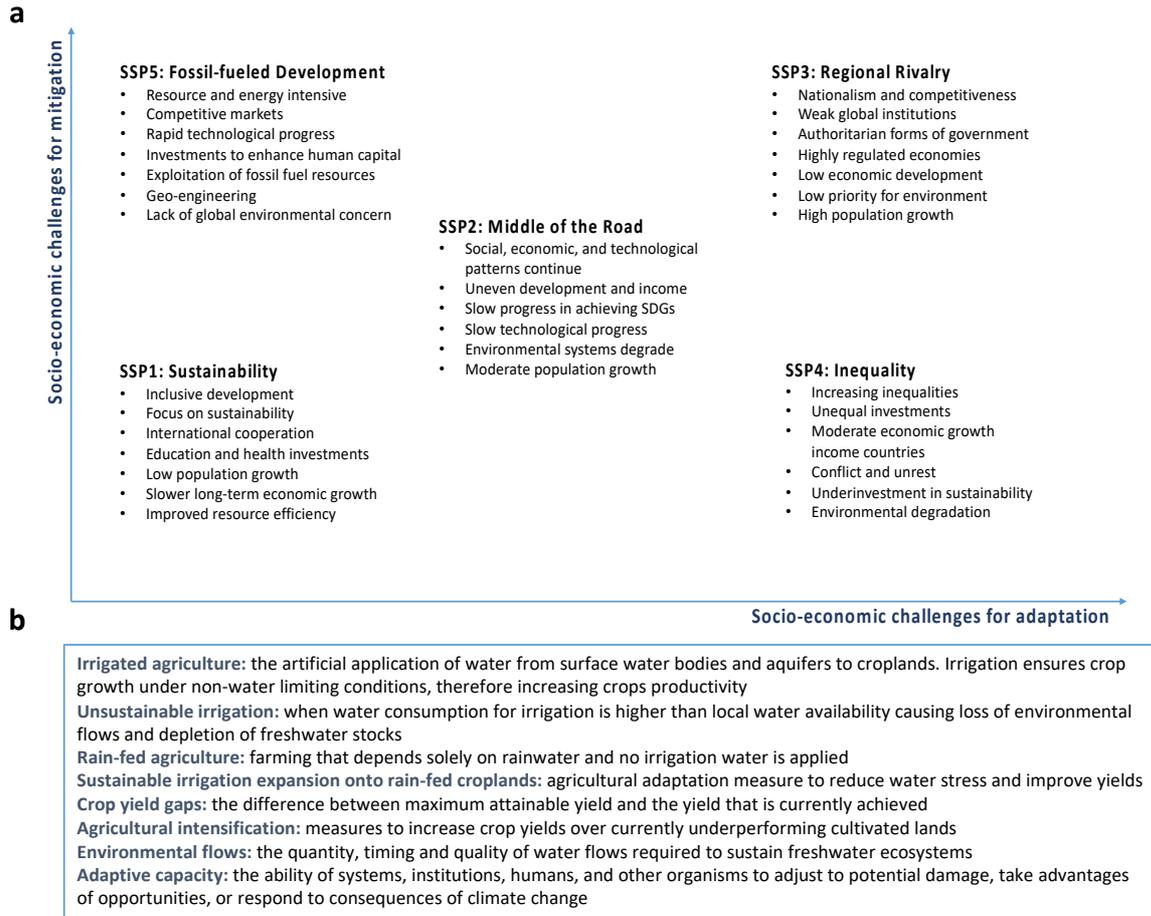


Fig. 1 | A conceptual framework of the Sustainable Irrigation Deployment Index. The formula of the index is displayed on the bottom left. We provide example input data from Ref⁸ for Russia and the United States of America because of their importance in global food production, to illustrate the components of the SIDI. The map shows the SIDI per country calculated with observed data from (circa) 2000.

The SIDI in a socioeconomic context | Quantitative assessments of irrigation deployment have been of high interest in the scientific community^{14–18}. Existing efforts to assess the future implementation of sustainable irrigation were mainly focused on biophysical factors by quantifying irrigation water requirements using climate, water or irrigation models, or on the influence of future technological advancements according to various scenarios^{2,8,19–21}. However, they do not account for country-specific socioeconomic conditions that, as key determinants of adaptive capacity, will enable or preclude irrigation deployment²². Moreover, some of the existing studies do not take into consideration the biophysical constraints for irrigation (e.g., Ref²⁰). Our study differs from existing analyses, as the focus is on assessing how socioeconomic variables (embedded within the SSP framework) will constrain or limit the biophysically sustainable irrigation potential. In order to comprehend and isolate these socioeconomic drivers to irrigation expansion, and to reduce further uncertainty related to projected climate impacts, we refrain from additionally including the effects of climate change on water availability and demand for irrigation in this study²³.

We embed the SIDI in the framework of the Shared Socioeconomic Pathways, five broad narrative-based scenarios of future socioeconomic developments (Box 1A). These scenarios have been developed as baseline trajectories for use in integrated assessments of climate change and socioeconomic developments. The five SSPs span a wide range of futures in terms of the socioeconomic challenges they imply for mitigation and adaptation¹¹. The SSPs serve as a basis for quantification of some of the key dimensions of the scenarios. Here we utilize this framework to calculate projections of potential sustainable irrigation expansion under socioeconomic change.



Box 1 | The Shared Socioeconomic Pathways and concepts and definitions about agriculture and irrigation.

(a) Narratives of distinct socioeconomic futures over the 21st century¹¹. The framework provides quantitative adaptation-relevant projections for population, education, urbanization, income, the Human Development Index²⁴, inequality²⁵, governance²⁶ and gender inequality²⁷. (b) Concepts and definitions of irrigated agriculture, unsustainable irrigation⁸, rain-fed agriculture, sustainable irrigation expansion, crop yield gaps^{6,28}, agricultural intensification⁶, environmental flows²⁹ and adaptive capacity²².

We test for different quantified socioeconomic dimensions of the SSPs to identify those that explain variations across countries in the current level of sustainable irrigation deployment, as proxied by the SIDI (see Tab. S2). Using a cross-sectional regression with SIDI as the dependent variable, socioeconomic determinants as independent variables, and controlling for the share of rain-fed crops in the total production, we find that governance³⁰ shows a significant relationship with the SIDI (see Methods). The share in current rain-fed agriculture (compared to the total sustainable calorie production) is expectedly relevant for the level of sustainable irrigation deployment, indicating that countries in which a high fraction of calorie production is currently met by rain-fed agriculture have implemented sustainable irrigation to a lesser extent. From a hydrological point of view, rainfed agriculture is also regarded as being sustainable, however, we assume it to be less resilient in the light of climate change. The significance of governance, on the other hand, indicates that countries with better institutions, less corruption and better regulatory quality (to name a few characteristics of what constitutes “good governance” according to the employed indicator²⁶) are also closer to their maximum sustainable crop yields. These relationships neither imply causation, nor does it imply that good

governance is the only driver of sustainable irrigation deployment. Our aim is to identify a statistical relationship that allows for an internally-consistent temporal extension of the SIDI within the SSP framework. GDP was also detected to have an effect on the current variation of the SIDI, but it becomes insignificant after the indicator of governance is introduced. The two identified predictors, namely the level of governance and the share of rainfed agriculture, are able to explain more than 70% in the current variations in used sustainable irrigation potential across the globe (Tab. S2).

Projecting sustainable irrigation deployment | The coefficient estimates from the regression model are applied on the governance projections²⁶ from the SSPs, which allows for future projections of the SIDI over the 21st century for each of these five scenarios, also taking into account the progression of the share in rain-fed agriculture at every time step as irrigation is deployed (see Methods). In Fig. 2A the global and regional development of the SIDI is displayed, with projections starting in 2020 and ending in 2100. The red dots in Fig. 2A display the SIDI that was quantified using data (Ref⁸) from 2000 and serve as reference points. Fig. 2B shows the regional differences for a Middle of the Road scenario (SSP2).

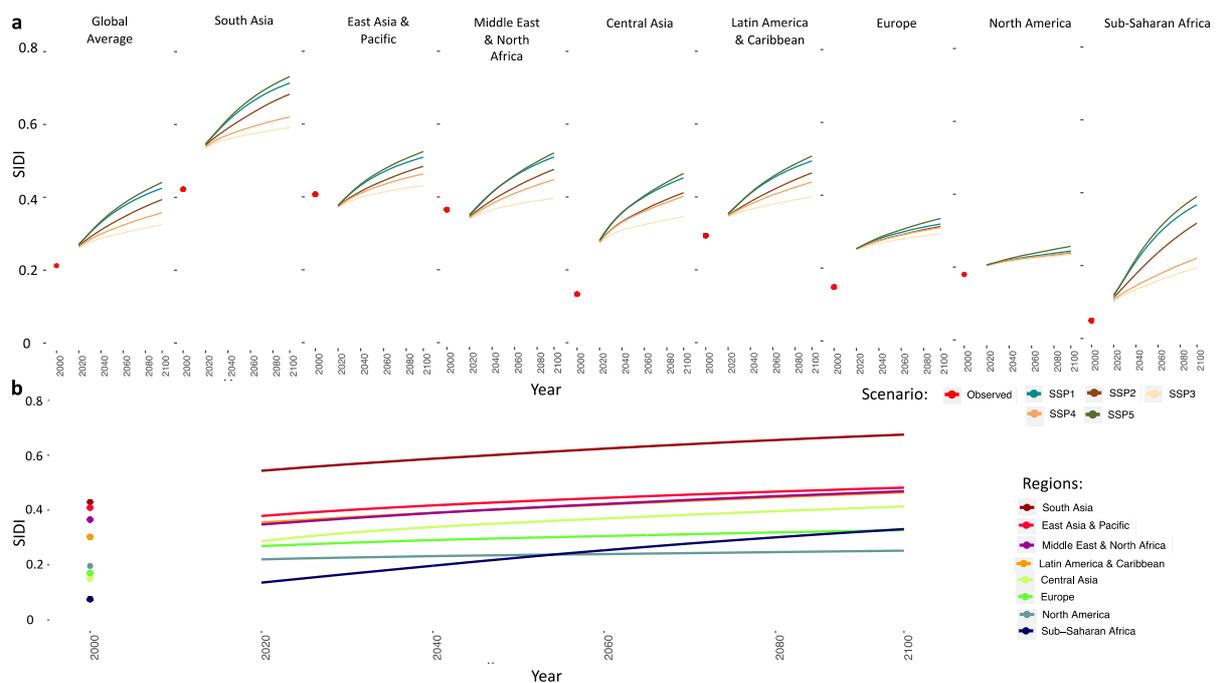


Fig. 2 | Projections of the Sustainable Irrigation Deployment Index. (a) Trajectories are shown for global and regional and for the different SSP-scenarios. (b) Regional projections of the SIDI for Middle of the Road scenario (SSP2). The data for 2000 (observed) is from Ref⁸ and the projections are shown from 2020 until 2100. The regional projections are displayed for the World Bank regions³¹ (delineation of the regions can be seen in Fig. 3).

The projections of the SIDI alongside the five SSPs display large heterogeneities between regions and scenarios. Globally and regionally (Fig 2A), SSP5 and SSP1 are the most optimistic scenarios, which is consistent with the scenario storylines, as governance reaches the highest levels in these two scenarios. SSP3, also in line with the storylines, is the most pessimistic scenario, displaying the smallest improvements for the index both globally and regionally. The global average SIDI for the year 2000 is estimated at 0.23 (Fig. 2A). This

indicates that only 23% of the global sustainable irrigation potential was being used at the beginning of the century. The global SIDI is projected to improve from 0.23 to 0.43 in a Sustainability scenario (SSP1) – which implies that globally 43% of the sustainable irrigation potential could be utilized by the end of the century. In contrast, in a Regional Rivalry scenario (SSP3), the SIDI would only improve to 0.34. In this scenario, we would only use 34% of the sustainable irrigation potential globally by the end of the century.

Regional results for the baseline SIDI vary largely (between 0.5 and 0.4) in year 2000 (Fig. 2B). South Asia has the highest SIDI in 2000, followed by East Asia & Pacific – both displaying results above 0.4. This indicates that, compared to other regions, these two are currently using a high fraction of their sustainable irrigation potential (around 40%) and therefore the ability of their agricultural sector to buffer precipitation variations via irrigation endows them with a relatively high adaptive capacity (Fig. 2A). Countries in this region, such as India or Pakistan, are known for their strong dependence on the agricultural sector and have already implemented large-scale irrigation systems in the past³², although this has led some of them to currently rely on unsustainable exploitation of water resources⁸. South Asia is the region closest to narrowing the yield gap by the end of the century, reaching an index of 0.70 in a Sustainability scenario (SSP1). In SSP3, South Asia will reach a SIDI of 0.58 in 2100.

In contrast, the region with the smallest SIDI in year 2000 is Sub-Saharan Africa (0.05), which indicates that the region is currently using very little of its sustainable irrigation potential. This is because most countries in the region do not yet have the possibility to access water management technologies and benefit from irrigation (i.e., face economic water scarcity⁵), even though irrigation has long been emphasized as a solution to intensify agricultural production, support rural economic development and enhance resilience to climate variability and change^{33,9}. This also relates to the low levels of governance (e.g. ineffective national bureaucracies), which has hindered large-scale irrigation projects in Sub-Saharan Africa in the past⁹. The projections of the SIDI emphasize the vast potential for improvement in the region. In a Sustainability scenario, Sub-Saharan Africa could reach a SIDI of 0.38 by 2100, a > 600% improvement compared to 2000 levels. In contrast, in SSP3 the SIDI of the region would not go above 0.21. As can be seen in Fig. 2B, Sub-Saharan Africa will reach the same SIDI levels as Europe by the end of the century in a Middle of the Road-scenario (SSP2).

The remaining regions (Central Asia, Europe, Latin America & Caribbean, Middle East & North Africa and North America) reached indices comparable to the global average (between 0.1 and 0.3) in year 2000. Regions such as Europe and North America are, despite their level of development, not yet using a lot of their sustainable irrigation potential and reach an index around 0.2. This is because most countries within that region rely heavily on rain-fed agriculture for their caloric production but have a reduced dependency on irrigated agriculture (under current climatic conditions). Moreover, Europe and North America already feature high levels of governance in the baseline period, which diminishes their sustainable irrigation expansion in our analysis.

People fed via sustainable irrigation | Future increase in sustainable irrigation as proxied by the SIDI and projected alongside the SSPs can be translated into potential calorie production and people fed. Fig. 3A shows the total people fed via sustainable irrigation in 2020, 2050 and 2100 within a region. The number of people fed is displayed for a Sustainability scenario (results for other SSPs can be deduced from Tab. S3). Fig. 3B shows the percentage increase from 2020 throughout the 21st century for the different SSP scenarios. Governance estimates are only available until 2095, therefore our projections also end in this year. However, we assume the same level of the SIDI and calories produced in 2095 and 2100, to match the population estimates.

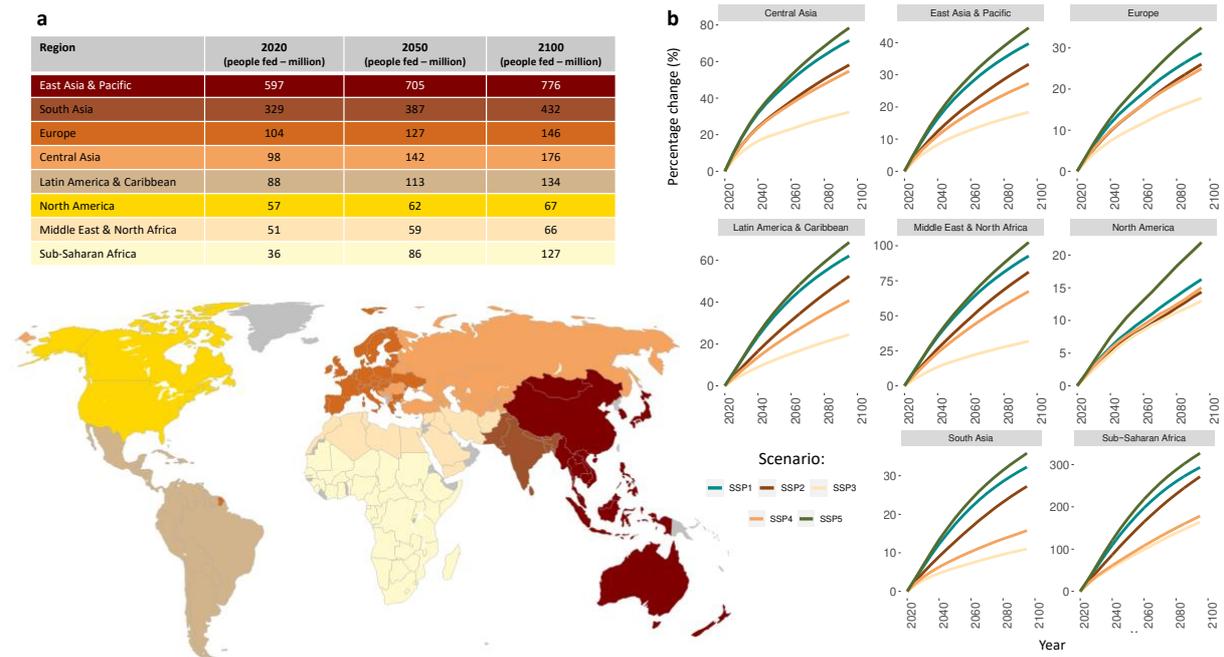


Fig. 3 | People fed via sustainable irrigation in 2020, 2050 and 2100. (a) Total amount of people fed per region in 2020, 2050 and 2100 via sustainable irrigation for the World Bank regions³¹ in SSP1 (people fed reported in million per year). (b) Percentage change in people fed via sustainable irrigation (per country) is also shown for the World Bank regions³¹ and the five SSP scenarios from 2020 until 2100. Results for the other SSPs can be found in Tab. S3.

According to our model estimates, the region East Asia & Pacific is currently able to produce the highest level of calories via sustainable irrigation in 2020 and feeds a total of 597 million people. South Asia is the region with the second highest calorie production, with a total of 329 million people being fed via sustainable irrigation in the same year. The lowest calorie production and number of people fed through sustainable irrigation is apparent for Sub-Saharan Africa and Middle East & North Africa (36 million and 51 million, respectively) (Fig 3).

The analysis shows that the regions in which a lower amount of people are fed via sustainable irrigation in 2020 are able to make the greatest improvements by 2100 in that regard. Sub-Saharan Africa, for example, will experience the highest percentage increase in people fed via sustainable irrigation, by more than 250% until 2100 (compared to 2020) in a Sustainability scenario. This would increase the total amount of people being fed via sustainable irrigation from 36 million people in 2020 to 127 million people by the end of the century (Fig. 3).

In contrast, East Asia & Pacific, the region with the highest amount of people fed via sustainable irrigation in 2020, will improve by around 30% until 2100 in a Sustainability scenario (SSP1). That percentage improvement would still increase the amount of people fed from 597 million people in 2020 to 776 million people by the end of the century in SSP1. This is the highest regional average in our analysis. Differences between the socioeconomic scenarios are less pronounced in regions with smaller relative improvement (e.g., a 3% difference between SSP1 and SSP3 in North America as opposed to 140% difference in Sub-Saharan Africa) (Fig. 3).

Tab. 1 | Total people fed globally with sustainable irrigation in 2020, 2050 and 2100, population projections and the fraction of people fed via sustainable irrigation per SSPP. Total people fed was quantified assuming a calorie intake of 3343 kcal per capita per day⁸. Population projections are for each SSP in the year 2100³⁴. People fed are displayed in billion per year.

Scenario	2020 (billion people)	2050 (billion people)	2100 (billion people)	Population in 2100 (billion people)	% fed in 2100
SSP1	1.36	1.68	1.93	6.88	28%
SSP2	1.34	1.58	1.80	9.00	20%
SSP3	1.32	1.46	1.54	12.6	12%
SSP4	1.33	1.54	1.71	9.27	18%
SSP5	1.35	1.70	1.98	7.36	27%

Globally, we find that in SSP1, sustainable irrigation could feed a total of 1.93 billion people by the end of the century (Tab.1). When relating this to the estimated population increase, we project that 28% of the global population could be fed via sustainably irrigated calories produced. In contrast, only 1.54 billion people could be fed via sustainable irrigation by the end of the century in a SSP3 scenario – which could feed 12% of the global population. The analysis shows that SSP1 and SSP5 will have the best chances at meeting projected global food demands, whereas SSP3 and SSP4 will face the highest challenges in reaching that objective (Tab. 1).

Fraction of yield gap closure level | In a yield gap closure scenario and using estimates from Ref⁸, a total of 4 billion people could potentially be fed via sustainable irrigation in the absence of socioeconomic constraints (See Tab. S1). However, our results show that socioeconomic factors are most probable to substantially constrain this potential. Even by the end of the century, in the most optimistic scenario (SSP1), only about half of the theoretically possible potential would be realized (about 2 billion people). 1.4 billion people are fed with sustainable irrigation in 2000, curtailing the future additional potential even further (compare Tab. 1). This underlines a growing need to incorporate socioeconomic projections into analyses of future food security².

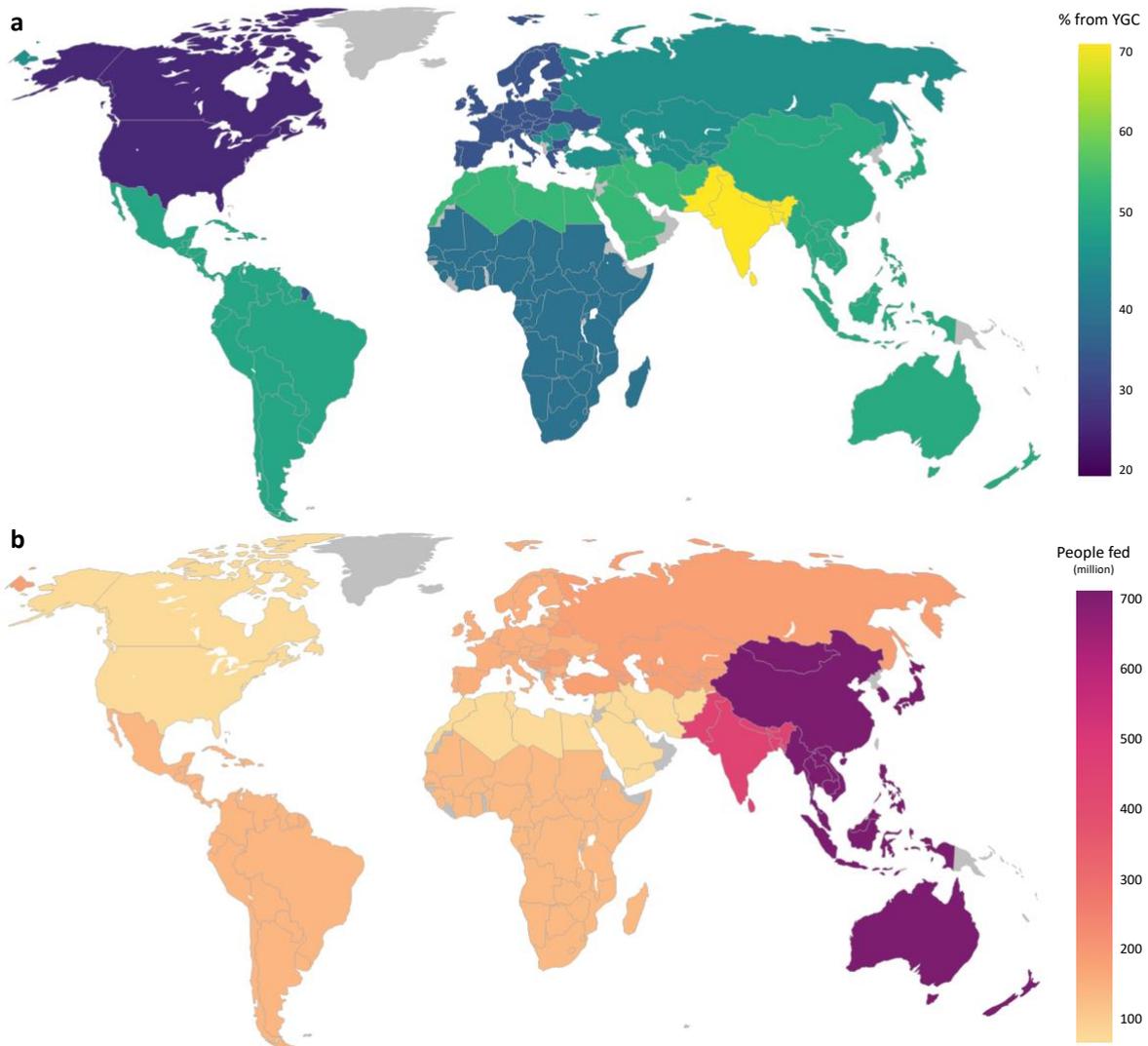


Fig. 4 | Projected sustainable irrigation potential used in a Sustainability scenario (SSP1) compared to a YGC scenario and people fed by the end of the century. (a) Percentage difference between projected sustainable irrigation calories produced in 2100 for a Sustainability scenario (SSP1) and sustainable irrigation calories produced in a YGC-scenario from Ref⁸. (b) Total amount of people fed per region (reported in million per year) via sustainable irrigation in 2100 for SSP1.

Fig. 4A compares yield gap closure potential under SSP1 with irrigation biophysical potentials. By 2100 under SSP1, South Asia will be able to use 70% of the irrigation yield gap closure potential, followed by the Middle East & North Africa (54%) and Latin America & Caribbean (49%). By contrast, panel B displays the amount of people per region that could be fed via sustainable irrigation by the end of the century for SSP1. While East Asia & Pacific is the country with the highest number of people fed (776 million), we find South Asia (432 million) and Central Asia (146 million people) to be countries with high sustainably irrigated calorie production and thus population fed, by the end of the century. Sub-Saharan Africa, which was the region with the lowest people fed in 2020, is projected to feed more people by the end of the century (127 million) than North America (67 million) and Middle East & North Africa (66 million). This shows, for example, that in Europe the number of people fed via sustainable irrigation is comparably high (146 million), while their yield gap remains substantial (33%

from YGC). By the end of the century, none of the regions will close the yield gap in neither of the scenarios. Nevertheless, substantial increases in people fed via sustainable irrigation can be recorded.

Irrigation in the context of climate change | Consistently with the SSP framework that by design does not account for impacts of future climate change, we also do not account for those in our projections¹¹. Both the SIDI and future estimates of sustainable irrigation potential were thus derived using present-day crop water requirements and surface water availability quantities. However, future calorie production and the sustainable irrigation expansion potential will be impacted by climate change through its alteration of precipitation amount and timing, the occurrence of extreme events³⁵, as well as changing soil moisture and crop water requirements²³. Changes in water availability and demand and higher exposure to heat extremes are, for example, projected to negatively impact local agricultural production and reduce potential benefits of CO₂ fertilization in the Mediterranean, Central America, the Caribbean, South Africa and Australia^{36,37}.

Implications for climate adaptation | Irrigation is one of the most prominently discussed adaptation measures to climate change⁵, however its negative consequences, including environmental flows impairment and depletion of freshwater stocks, are not always acknowledged. Understanding the potential for sustainable expansion of irrigation is essential, as climate change adaptation will likely drive a substantial expansion of this technology. In addition, the multiple facets of socioeconomic development that determine a countries' capacity to tap into existing sustainable irrigation potentials remains largely ignored in this context. Our scenarios do not explicitly represent the impacts of climate change that would provide a perspective on the need for irrigation expansion as an adaptation measure. But they illustrate what socioeconomic constraints may exist to its successful implementation, as for many world regions irrigation expansion would already be a highly effective adaptation measure under current climate conditions. They highlight that even existing and well-established technologies such as irrigation may be limited in their availability to alleviate impacts at higher levels of warming. It is important to highlight that our scenarios do not provide an upper limit of what could be possible in terms of irrigation deployment as a climate adaptation measure, but that other factors, which we were not able to include in our analysis, could further enable the implementation of sustainable irrigation. Overcoming socioeconomic constraints to improve adaptation deployment under climate change is a distinct possibility, and in some cases might be a necessity to prevent substantial reductions in agricultural productivity²³. Our findings highlight that this might be all but easy given the observed evidence of socioeconomic factors limiting the effectiveness of irrigation deployment⁹.

Discussion | By introducing the Sustainable Irrigation Deployment Index we assess how socioeconomic conditions are related to the current level of sustainable irrigation with respect to its potential under a yield gap closure scenario. In our analysis, a governance indicator – defined as the institutional capacity of countries – emerges as a socioeconomic factor that best explains the current level of sustainable irrigation deployment. Our findings on the importance of governance and institutions as key conditions for the successful deployment of such

adaptation options are in line with other findings on indices reflecting adaptive capacity⁹. The two identified predictors, namely the level of governance and the share of rainfed agriculture, are able to explain more than 70% in the current variations in used sustainable irrigation potential across the globe. By comprehending which factors currently hinder or enable sustainable irrigation, we are able to project the evolution of sustainable irrigation deployment throughout the 21st century alongside the socioeconomic development of countries.

Socioeconomic constraints that currently limit sustainable irrigation expansion are particularly prominent in regions such as Sub-Saharan Africa, where less than 1% of the sustainable irrigation potential is currently being used. Due to the currently low levels of socioeconomic development, it will and has been more challenging to introduce new farming approaches, such as retaining rainwater for irrigation. This is in line with findings from Ref¹², who report that the implementation of irrigation systems, despite large-scale investments in its infrastructure, were hindered by centralized bureaucracies, lacking technical expertise and political incentives⁹. However, in regions where most of the population growth is expected to occur in the coming decades, it will be crucial to reach much higher levels of adaptive capacity in the agricultural sector, to counteract already existing hunger and malnutrition. For example, in the Sahel region, where less than 4% of cropland is currently equipped with any kind of irrigation infrastructure and where population growth is already outstripping food supply, population is expected to more than double to 450 million by 2050³⁸. International and local efforts need to focus on increasing adaptive capacity in these regions, as well as specific support for irrigation deployment in the agricultural sector, to support the well-being of hundreds of millions of people.

The findings presented in this study can be useful for impact or crop models that assess potential future crop yields. While sustainable freshwater constraints are increasingly considered in such modelling efforts³⁹, socioeconomic considerations limiting irrigation deployment are so far not consistently implemented. Our projections also provide important entry-points to include information on the future climate resilience and adaptive capacity for policy-making in integrated assessment models (IAMs). We report a substantial scenario dependence of future sustainable irrigation expansion which underscores the need to incorporate socioeconomic variables into projections of future agricultural developments. This study provides a starting point for the analysis of other adaptation options, such as crop migration⁴⁰, or for other sectors in which adaptation will be determining for climate resilience (e.g., reservoirs planning for irrigation). Assessing the future adaptive capacity of countries and including this information in impact assessments will be of key importance to assess pathways to climate resilience. The capacity of countries to ensure food security in the context of rapidly changing biophysical conditions will be one of the major determinants for the next century⁴¹. In summary, our results show that by improving the socioeconomic conditions (e.g., governance) of countries, we will move closer to reaching the Sustainable Development Goal (SDG) of zero hunger and other highly relevant and interrelated SDGs, highlighting their interconnectedness and the importance of a holistic sustainability agenda⁴².

Methods

The Sustainable Irrigation Deployment Index (SIDI) builds on previous work by Rosa et al (2018). We use the data estimates of calorie production under current conditions and in the case of maximized crop production by alleviation of water limitations (called the yield gap closure, or YGC scenario). Using a global process-based crop water model⁴³, Rosa et al (2018) assessed crop water requirements to reach yield gap closure, i.e. the amount of irrigation water needed to complement input from precipitation so as to ensure sufficiently high soil moisture levels and satisfy the crop evapotranspirative demand. They used spatially distributed information on rain-fed/irrigated yields and harvested areas in year 2000 from Monfreda et al (2008) and Portmann et al (2010), respectively. They first calculated evapotranspiration for each day, crop and grid cell for both rainfed and irrigated cases. The daily irrigation water requirements to reach YGC were then calculated as the difference between the two, and aggregated over a year. They compared the irrigation water demand to local renewable freshwater availability (for both human water use and environmental flows) to identify regions of the world where irrigation can be expanded into currently rain-fed croplands without threatening freshwater ecosystems and depleting freshwater stocks. The analysis was conducted at the pixel level, we aggregated their results to the country- and region-level.

The Sustainable Irrigation Deployment Index. We derive the calories that are currently produced via sustainable irrigation from the estimates of Rosa et al. (2018) of total calories produced via irrigation as well as their unsustainable share in 2000 (see Equation 1 and Tab. S1). We then use their estimates of total irrigation calories produced via irrigation under a yield gap closure scenario (YGC_irr), the additional calories that would be produced via unsustainable expansion or intensification under YGC (YGC_irr^u) and the calories currently produced via unsustainable irrigation (C_irr^u) to assess the potential gain under YGC by implementing sustainable irrigation (Equation 2). The amount of calories produced under YGC also includes those being currently produced. All estimates are reported in 10¹⁵ kcal per year, the full table can be found in the supplementary material (Tab.S1).

$$(1) \text{ Current sustainable irrigation} = C_{\text{irr}} - C_{\text{irr}}^u$$

$$(2) \text{ Sustainable irrigation under YGC} = YGC_{\text{irr}} - YGC_{\text{irr}}^u - C_{\text{irr}}^u$$

The SIDI is then derived following:

$$(3) \text{ Sustainable irrigation deployment index (SIDI)} = \frac{\text{Current sustainable irrigation}}{\text{Sustainable irrigation under YGC}}$$

Linear model of the present-day SIDI. After deriving the SIDI for each country under current conditions, we calculated the mean GDP⁴⁴⁻⁴⁶, population³⁴, urbanization⁴⁷, and governance²⁶ over the 1995-2005 time period. Our approach aims to explain between-country variation in the SIDI with a linear regression model using the above-mentioned socioeconomic variables as predictors. Details on the coefficients and significance associated with each variable are included in the supplementary materials (Tab. S2). Our final model specification expresses

SIDI as a function of the share of calories produced via rain-fed agriculture (Share_rainfed) and governance:

$$(4) \text{SIDI}_{i,t} = \beta_0 + \beta_1 \text{Share_rainfed}_{i,t} + \beta_2 \text{Governance}_{i,t} + \varepsilon_{i,t}$$

where i denotes country, t denotes time (year), β_0 is the intercept, coefficients β_1 and β_2 are the coefficient estimates for the covariates and $\varepsilon_{i,t}$ is the robust standard error.

SIDI projections. Keeping the β coefficients constant, we derive projections for the SIDI by using estimates of the future evolution of the governance index for each of the five SSP scenarios (see Table 2 in the SM), as well as computing that of the future share of rain-fed agriculture for every 5 years. Future governance estimates are available until 2095, therefore our projections also end in this year.

Governance projections were unavailable for some countries, which were thus removed from the analysis: Angola, Afghanistan, Albania, Myanmar, Montenegro, State of Palestine, Timor-Leste and China Taiwan. Furthermore, a few countries for which our linear model returns a negative SIDI in the year 2020 have been removed: Central African Republic, Democratic Republic of the Congo, Eritrea, Guinea, Guinea-Bissau, Liberia, Sudan, Somalia, Chad and Togo. In total, projections of the SIDI and associated calories were calculated for 130 countries.

Share in rain-fed agriculture. The share of rainfed agriculture in the total calorie production was found to have the highest explanatory power over variations in the SIDI across countries. It is defined as:

$$(5) \text{Share_rainfed} = \frac{C_rain}{(C_irr - C_irr^u) + C_rain}$$

Where C_rain denotes the current (2000) calories produced with rain-fed agriculture. C_rain and C_irr^u are projected to stay constant in a YGC scenario, as we do not account for the impacts of future climate changes (please see Fig. S3). However, since Share_rainfed evolves along with the number of calories produced via sustainable irrigation, we calculate it analytically for each time step (every 5 years, see SM for more information).

Calories. To assess the calorie production through sustainable irrigation over time, we multiply SIDI estimates at a time t with the calories produced via sustainable irrigation in a YGC-scenario, following Equation 6:

$$(6) \text{Calories}(t) = \text{SIDI}(t) * \text{YGC_irr}$$

Calculation of additional people fed in a given scenario and for a specific year requires an estimation of caloric intake per person. Rosa et al (2018) calculated the daily calorie requirements equivalent to a diet with 20% animal products by assessing the caloric and protein contents of each crop. After accounting for conversion efficiency, they arrived at an estimate

of 3343 vegetal kcal required per capita and per day. For each SSP, we calculate the sum of all calories produced in 2020, 2050 and 2100 in all countries using Equation 7 to arrive at global values. To assess the additional people fed, we subtract the number of people fed in 2020 from the corresponding 2050 and 2100 estimates. The average calories were then averaged over the World Bank regions³¹. Further, the percentage increase in sustainable calorie production compared to 2020 and up until 2100 was calculated as:

$$(7) \text{ Percentage increase} = 100 * \frac{(\text{calories_projected}(t) - \text{calories_2020})}{\text{calories_2020}}$$

The total amount of people fed at YGC globally (~4 billion) was quantified from the dataset by Rosa et al (2018) by summing the maximum calories produced (for the same countries as in this analysis), dividing the calories by 365 days (to arrive at the per day estimate) and further dividing the result by 3343 vegetal kcal to arrive at the total people that can be fed at YGC. The same method was applied to quantifying the total amount of people fed via sustainable irrigation at the end of the century for the different SSPs (~2 billion).

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Keywords: irrigation, sustainability, food security, adaptation, climate change, SSPs

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Data availability: Data and code are available at Github
(https://github.com/nicolenicolen/Sustainable_irrigation_2021)

Author contribution: The research was designed by NvM, MA and C-FS. NvM performed the analysis and created the display items. LR provided the data for the underlying study. NvM led the writing of the manuscript with contributions of MA, C-FS, LR and QL.

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Figures

Russia: Russia's agriculture is largely rainfed. Irrigated agriculture provides only about 5% to the current total calorie production. Under YGC, Russia's total production could almost triple, driven by sustainable irrigation expansion. The country reaches a SIDI of 0.03.

United States of America: Agriculture in the United States of America is largely rainfed. Irrigated agriculture provides about 20% to the current total calorie production. Under YGC, this could increase to more than 50%. The country reaches a SIDI of 0.34.

The Sustainable Irrigation Deployment Index (SIDI) describes how much of its sustainable irrigation potential a country is using in the year (circa) 2000. If the index value is one, a country produces the maximum yield that can be attained through the deployment of sustainable irrigation quantities. If the index value is zero, a country is not yet using any of its sustainable irrigation potential.

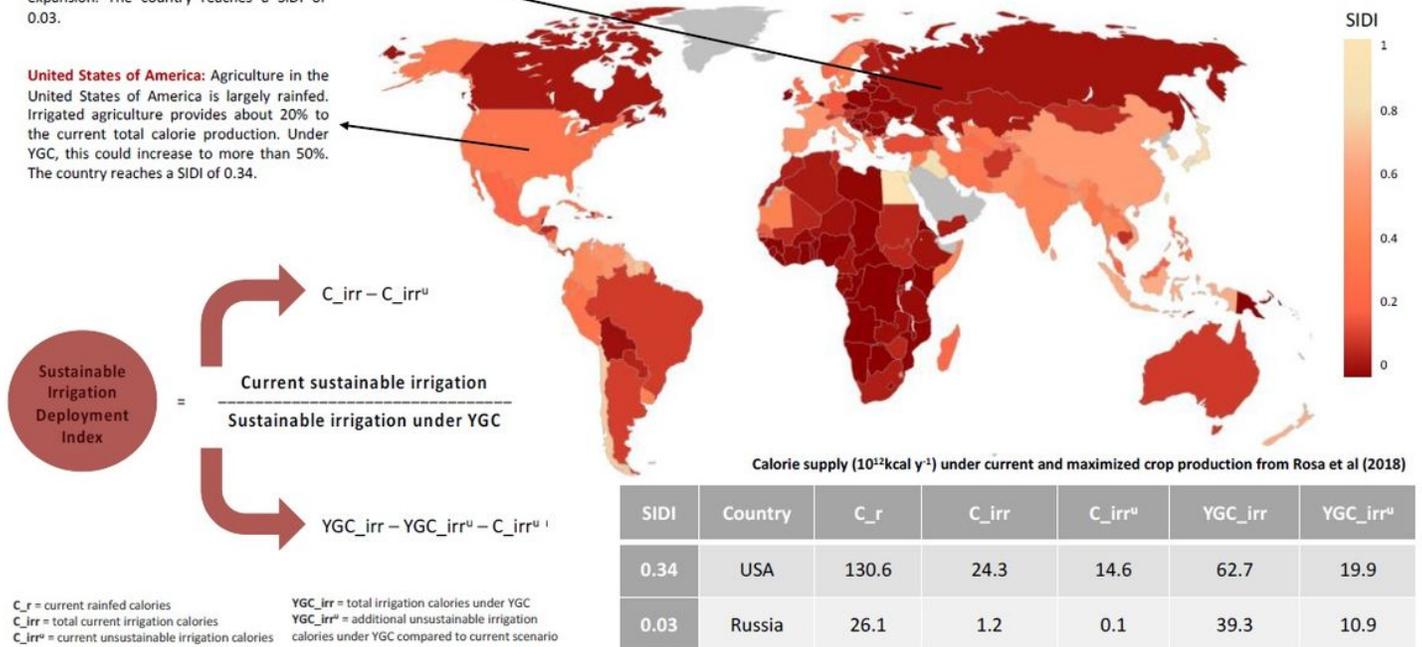


Figure 1

A conceptual framework of the Sustainable Irrigation Deployment Index. The formula of the index is displayed on the bottom left. We provide example input data from Ref8 for Russia and the United States of America because of their importance in global food production, to illustrate the components of the SIDI. The map shows the SIDI per country calculated with observed data from (circa) 2000. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

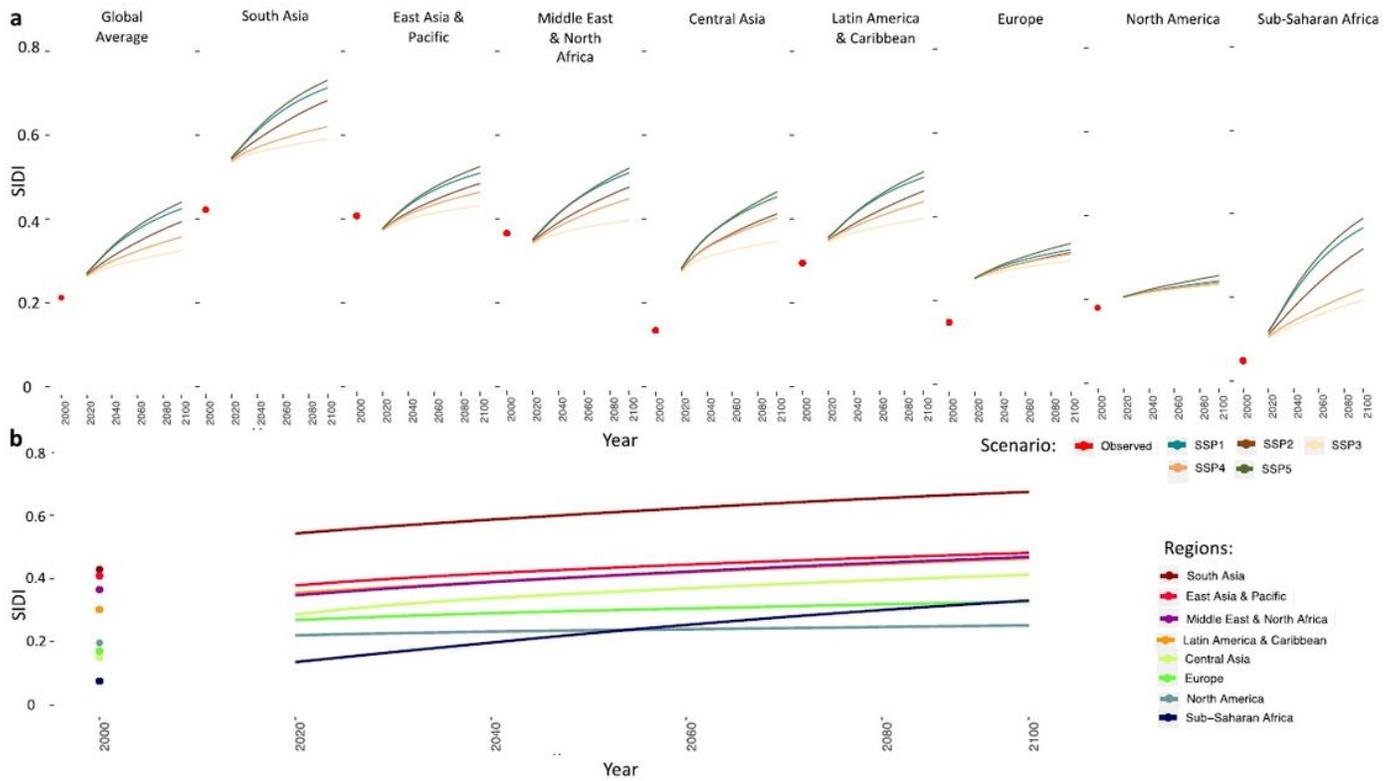


Figure 2

Projections of the Sustainable Irrigation Deployment Index. (a) Trajectories are shown for global and regional and for the different SSP-scenarios. (b) Regional projections of the SIDI for Middle of the Road scenario (SSP2). The data for 2000 (observed) is from Ref8 and the projections are shown from 2020 until 2100. The regional projections are displayed for the World Bank regions³¹ (delineation of the regions can be seen in Fig. 3).

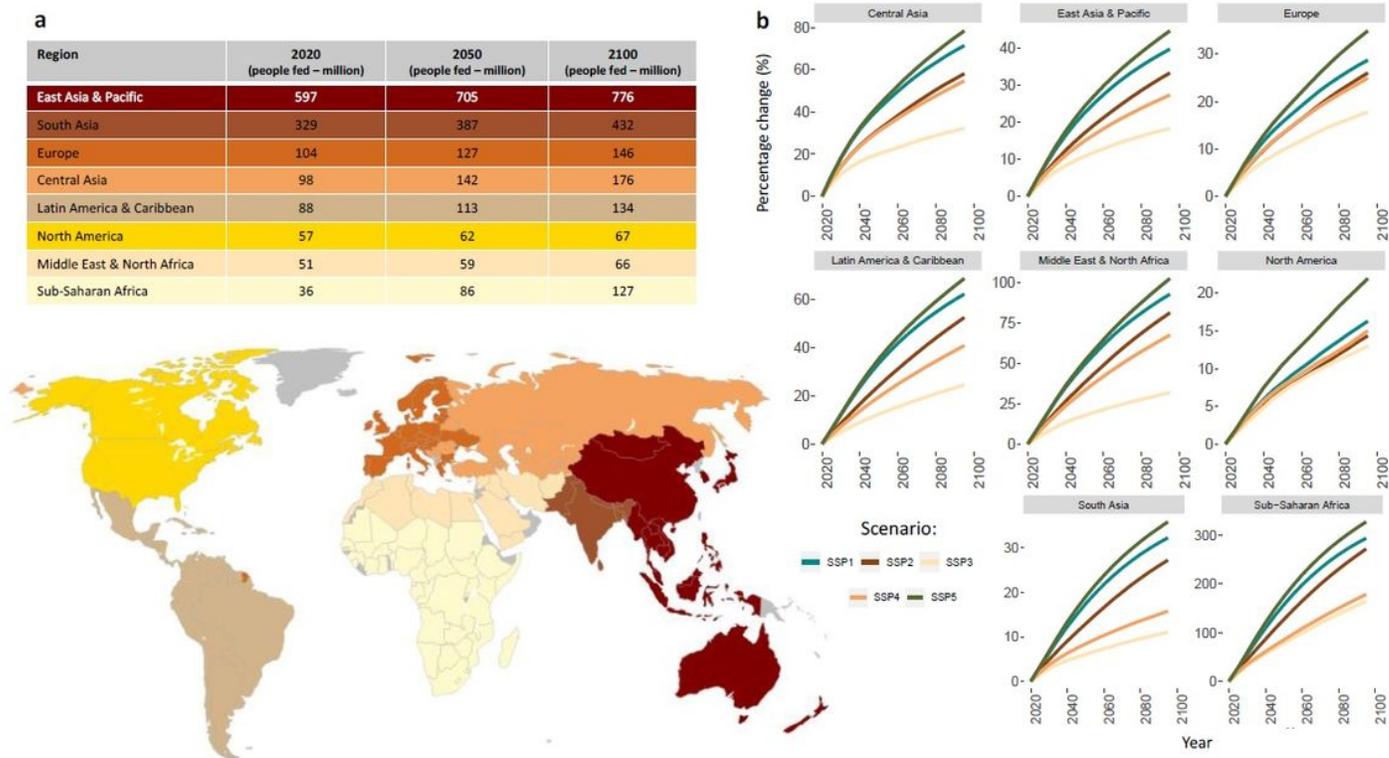


Figure 3

People fed via sustainable irrigation in 2020, 2050 and 2100. (a) Total amount of people fed per region in 2020, 2050 and 2100 via sustainable irrigation for the World Bank regions³¹ in SSP1 (people fed reported in million per year). (b) Percentage change in people fed via sustainable irrigation (per country) is also shown for the World Bank regions³¹ and the five SSP scenarios from 2020 until 2100. Results for the other SSPs can be found in Tab. S3. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

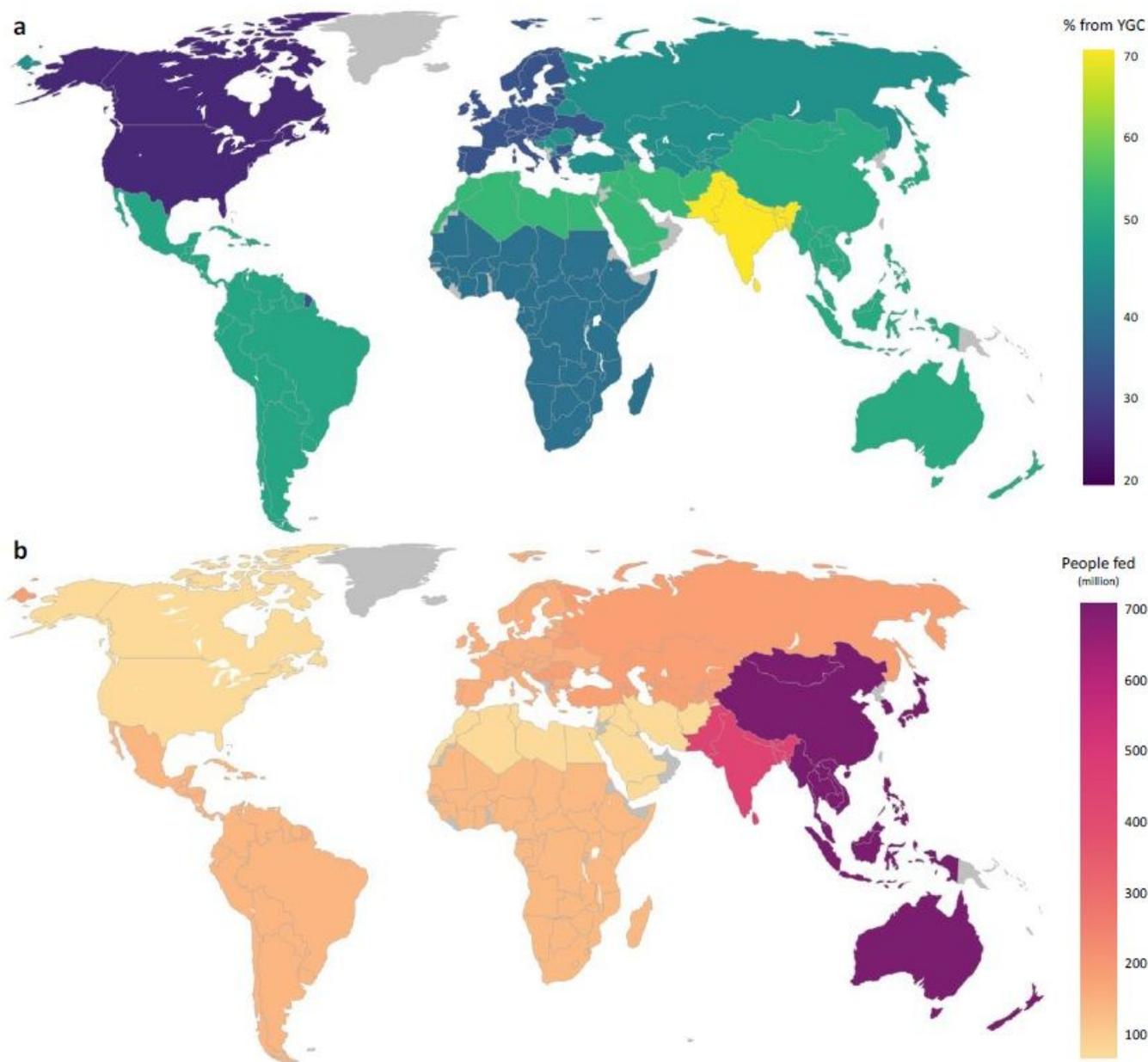


Figure 4

Projected sustainable irrigation potential used in a Sustainability scenario (SSP1) compared to a YGC scenario and people fed by the end of the century. (a) Percentage difference between projected sustainable irrigation calories produced in 2100 for a Sustainability scenario (SSP1) and sustainable irrigation calories produced in a YGC-scenario from Ref8. (b) Total amount of people fed per region (reported in million per year) via sustainable irrigation in 2100 for SSP1. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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