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Accounting for socioeconomic constraints in sustainable irrigation expansion assessments

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Abstract

Sustainable irrigation expansion over water limited croplands is an important measure to enhance agricultural yields and increase the resilience of crop production to global warming. While existing global assessments of irrigation expansion mainly illustrate the biophysical potential for irrigation, socioeconomic factors such as weak governance or low income, that demonstrably impede the successful implementation of sustainable irrigation, remain largely underexplored. Here we provide five scenarios of sustainable irrigation deployment in the 21st century integrated into the framework of Shared Socioeconomic Pathways, which account for biophysical irrigation limits and socioeconomic constraints. We find that the potential for sustainable irrigation expansion implied by biophysical limits alone is considerably reduced when socioeconomic factors are considered. Even under an optimistic scenario of socio-economic development, we find that additional calories produced via sustainable irrigation by 2100 might reach only half of the maximum biophysical potential. Regions with currently modest socioeconomic development such as Sub-Saharan Africa are found to have the highest potential for improvements. In a scenario of sustainable development, Sub-Saharan Africa would be able to almost double irrigated food production and feed an additional 70 million people compared to 2020, whereas in a scenario where regional rivalry prevails, this potential would be halved. Increasing sustainable irrigation will be key for countries to meet the projected food demands, tackle malnutrition and rural poverty in the context of increasing impacts of anthropogenic climate change on food systems. Our results suggest that improving governance levels for example through enhancing the effectiveness of institutions will constitute an important leverage to increase adaptive capacity in the agricultural sector.

1. Introduction

More than 900 million people were severely food insecure in 2020 (FAO \textit{et al} 2021). 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 2050 (Beltran-Peña \textit{et al} 2020). At the same time, climate change has and is expected to change rainfall patterns and further exacerbate existing water- and heat-stress for rain-fed agricultural systems (Mbou \textit{et al} 2019, Valipour \textit{et al} 2021). Irrigation expansion, despite its documented environmental and hydroclimatic implications (Foster \textit{et al} 2018, Pulido-Bosch \textit{et al} 2018), 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 some of the negative impacts of temperature extremes on crops (Thiery \textit{et al} 2017,
Rosa et al 2020a, Droppers et al 2021, Caretta et al 2022, Rosa 2022). Irrigation will also have an important role in the sustainable intensification of agriculture, an effort to halt agricultural expansion by increasing crop yields in underperforming cultivated lands (Mueller et al 2012, Rosa et al 2018, Droppers et al 2021). However, half of the global irrigation practices are unsustainable at the beginning of the century (Rosa et al 2019) (box 1). Irrigation is regarded as sustainable when water withdrawals for irrigation do not exceed environmental flow requirements (box 1) nor deplete groundwater resources. 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 sustainably (Rosa et al 2018, Beltran-Pea et al 2020). It was estimated that the sustainably irrigated calorie production could almost double if the total biophysical potential for sustainable irrigation was to be exploited fully (Rosa et al 2018).

Due to the relevance for food security and the increasing vulnerability from climate change, quantitative assessments of irrigation deployment have received increasing attention (Faurès et al 2002, Rost et al 2009, Jägermeyr et al 2017, Nachtergaele et al 2020, Puy et al 2020). Existing efforts to assess future sustainable irrigation expansion 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 (Döll and Siebert 2002, Graham et al 2018, Rosa et al 2018, Beltran-Pea et al 2020, Hurtt et al 2020). The existing studies did not account for country-specific socioeconomic conditions that, as key determinants of adaptive capacity (box 1), will enable or preclude sustainable irrigation deployment. Thus far, socioeconomic factors (e.g. governance or income) tend to be overlooked in quantitative assessments of potential future irrigation deployment, including climate impact models, thereby assuming optimal or maximum possible irrigation and thus potentially overstating its benefits (Holman et al 2019). Other analyses have indeed argued that, apart from biophysical or technological factors, irrigation is largely limited by institutional and economic capacity (Rosa et al 2020a, Rosa 2022).

The lack of irrigation due to limited institutional and economic capacity instead of hydrologic constraints is referred to as economic water scarcity (Rosa et al 2020a, Rosa 2022). Social, political, and economic factors are considered to be the most crucial factors influencing future sustainable irrigation development (Higginbottom et al 2021). However, global studies that consider biophysical and socio-economic constraints in an integrated fashion are currently missing.

Box 1. Concepts and definitions of irrigated agriculture, unsustainable irrigation (Rosa et al 2018), rain-fed agriculture, sustainable irrigation expansion, crop yield gaps (Lobell et al 2009, Mueller et al 2012), agricultural intensification (Mueller et al 2012), environmental flows (Jägermeyr et al 2015) and adaptive capacity (IPCC 2014).

Irrigated agriculture: the artificial application of water from surface water bodies and aquifers to croplands. Irrigation ensures crop growth under water limiting conditions, therefore increasing crops productivity

Unsustainable irrigation: when water consumption for irrigation is higher than local water availability causing loss of environmental flows and depletion of freshwater stocks

Rain-fed agriculture: farming that depends solely on rainwater and no irrigation water is applied

Sustainable irrigation expansion onto rain-fed croplands: expansion of irrigation onto rain-fed croplands when renewable blue water availability is sufficient to sustain crop production while preventing loss of environmental flows and depletion of freshwater stocks

Crop yield gaps: the difference between maximum attainable yield and the yield that is actually achieved

Agricultural intensification: measures to increase crop yields over currently underperforming cultivated lands

Environmental flows: water flows that, due to their quantity, quality and temporal variations, allow for sustaining freshwater ecosystems

Adaptive capacity: the ability of systems, institutions, humans, and other organisms to adjust to potential damage, take advantages of opportunities, or respond to consequences of climate change

In this study we assess the difference between the actual crop yield and the maximum potential yield that could be achieved by deploying sustainable irrigation (Mueller et al 2012). Relying on data by Rosa et al (2018), we design and introduce the Sustainable Irrigation Deployment Index (SIDI). The SIDI reflects the gap of how much of its domestic sustainable irrigation potential a country is currently using in comparison to what could be possible under maximum sustainable irrigation deployment. We assume that the extent to which this gap is closed today depends on the societally enabling factors (we refer to this property as adaptive capacity), which in turn is a product of various socioeconomic resources (Klein et al 2014). It is important to highlight that this conceptual approach does not attempt to resemble the actual (technical) implementation of irrigation. Rather, it aims to reflect the capacity of countries, the socio-economic enabling or hindering conditions affecting the actual implementation. Doing so allows us to explore how sustainable irrigation expansion might co-evolve with socio-economic development over the 21st century reflected in the Shared Socioeconomic Pathways (SSPs) (O’Neill et al 2017; figure S4). Utilizing the SSP framework enables us to also compare our findings for sustainable irrigation
with population projections over the 21st century to deduce the number of people whose food demand could be covered by future sustainable deployment.

2. Methods

To identify socioeconomic constraints to sustainable irrigation expansion and allow for a valuable and consistent projection of sustainable irrigation expansion, we establish an index that captures the gap between current level of sustainable irrigation and optimal level of sustainable irrigation. Rosa et al (2018) assessed whether and where freshwater availability is sufficient to sustainably close the yield gap on cultivated lands. They provide quantitative information on the current level of sustainable and unsustainable irrigation practices per country and estimate maximum attainable yields. To our knowledge, this is the only analysis that provides a global dataset which allows us to investigate and explore the gap between current and potential sustainable irrigation. Our analysis therefore relies on the data provided in the named study. While Rosa et al (2018) provide information on the current and potential future sustainability of irrigation accounting only for the biophysical availability of land and water, our study develops scenarios on how to reach that maximum potential while also accounting for socioeconomic constraints.

2.1. SIDI

The SIDI is the ratio between the current calorie production via sustainable irrigation and the maximum potential calorie production that could be attained at yield gap closure (YGC) by deploying sustainable irrigation (figure 1). In this analysis YGC is understood as the maximum yield attainable by relieving water limitation via irrigation deployment compatible with a sustainable use of freshwater resources (box 1). We acknowledge that other factors, such as nutrient supply, can also limit crop productivity (Mueller et al 2012). However, water remains a critical input limiting food production today (Rosa et al 2020a) and is thus the research subject of this study. We hence consider the yield gap to be closed when there is no difference between the potential sustainable irrigation and the actual sustainable irrigation of countries, and thus the full potential is being exploited (SIDI = 1).

Specifically, we use country-specific estimates from Rosa et al (2018) on calories produced via current irrigation ($C_{irr}$), calories produced via irrigation in a YGC scenario ($YGC_{irr}$), the calories currently unsustainably produced via irrigation ($C_{irr}^u$) and those produced unsustainably in a YGC scenario ($YGC_{irr}^u$). The calorie content for all 16 crop types was derived from the Food and Agricultural Organization (FAO) ‘Nutritive Factors’ database (FAOSTAT 2012). Irrigation is regarded as unsustainable when water consumption for irrigation is higher than local water availability (after deducing water for environmental flows and municipal and industrial human activities) which puts environmental flows at risk and depletes groundwater resources (box 1). By utilizing that data, we can assess the current calories produced via sustainable irrigation (1) and the calories that could be produced via sustainable irrigation in a YGC scenario (2). Equations (1) and (2) are used to calculate the SIDI (3). All estimates are reported for year 2000 in $10^{15}$ kcal yr$^{-1}$, the full table can be found in the supplementary material (SM) (table S2)

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

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

$$\text{Sustainable Irrigation Deployment Index (SIDI)} \quad = \quad \frac{\text{Current sustainable irrigation}}{\text{Sustainable irrigation at YGC}}. \quad (3)$$

$YGC_{irr}$ consists of the total calories that are produced around year 2000 ($C_{irr}$) via irrigation (sustainable and unsustainable) and the additional calories that could be produced via irrigation in a YGC scenario (sustainable and unsustainable). As our analysis concentrates on sustainable irrigation, we subtract $C_{irr}^u$ for current sustainable irrigation calories (1) and for sustainable irrigation calories at YGC (2) as it is included in $C_{irr}$ and $YGC_{irr}$ (table S2).

2.2. The SSPs

For our analysis we deploy the framework of the SSPs, five broad narrative-based scenarios of future socioeconomic developments over the 21st century (see figure S4). These qualitative storylines, which have been developed as baseline trajectories for use in integrated assessment of climate change, are hypothetical futures and aim to keep the number of socioeconomic pathways manageable by simplifying the complexity of drivers of mitigative and adaptive capacity (O’Neill et al 2017). The trajectories of some of the adaptation-relevant dimensions in the SSP framework have been quantified, for example gross domestic product (GDP) (Crespo Cuaresma 2015, Dellink et al 2017, Leimbach et al 2017) or population (Samir and Lutz 2017). The SSPs thus constitute a quantitative tool that can be used to frame
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 Rosa et al (2018) 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.

2.3. A statistical model for the SIDI

The between-country variation in the SIDI is explored through a limited set of socioeconomic indicators for which trajectories along the SPS have been quantified. The socioeconomic indicators that are quantified under the SSPs include governance (Andrijevic et al 2019), GDP (Crespo Cuaresma 2015, Dellink et al 2017, Leimbach et al 2017), population (Samir and Lutz 2017), urbanization (Jiang and O’Neill 2014) and gender inequality (Andrijevic et al 2020a). Our analysis is bound to these variables in order to deliver an internally consistent set of projections. It is important to highlight that the purpose of this linkage is not to identify causal mechanisms, or even the best statistical model to describe SIDI based on country level indicators, but to identify a statistical relationship between the level of sustainable irrigation and countries’ socioeconomic conditions reflected in the SSPs. Under the albeit strong assumption that the identified relationship in present day holds in the future, this approach allows for projections of the SIDI alongside the SSP trajectories until 2100.

In addition to the socioeconomic factors, we include the share of rain-fed calories in the total production (Share_rainfed) as a proxy of the extant prevalence of irrigation uptake in countries. In alignment with theories of technology diffusion (Comin and Hobijn 2010, Lybbert and Sumner 2012), we assume that for countries with a lower prevalence of irrigation in the baseline period there is a slower uptake of irrigation in the future as it is less ‘common’. The concept of technology diffusion aims to capture a range of societal dimensions including regulatory framework, subsidies, cultural, or societal network effects that contribute to technological uptake. In general, adaptation measures in the agricultural sector are more widely and more efficiently implemented when surrounding farmers have already successfully applied them, exhibiting an interdependence within geographical neighborhoods and between the adaptation measures chosen (Brown et al 2018, Mainardi 2021, Marton and Storm 2021). Neighborhood effects and social behavior have been documented to specifically influence irrigation uptake (Genius et al 2013, Tsusaka et al 2015). We therefore include this term here to accommodate the different uptake of irrigation within countries that might provide for very diverse starting points for potential future expansions in addition to the socioeconomic conditions (see e.g. very high irrigation levels in Egypt, Iraq and several East Asian countries as a result of the prevalence of these practices since millennia).

We apply a generalized linear model and investigating all possible combinations of the covariates with our index (table S1). In total, we considered 63 combinations and compared their validity. The best
performing model was selected based on three criteria. Firstly, we analyze how the effects of the predictors change throughout the various models. Secondly, we looked at the Akaike Information Criterion (AIC), which analyses the relative quality of statistical models by estimating the prediction error. The model with the lowest AIC, i.e. which demonstrates the best fit, was selected. Thirdly, we examined the $R^2$-value of the model, which demonstrates the percentage of the variance in the dependent variable that the independent variables explain collectively.

Based on these criteria, we have selected the model with SIDI as the dependent variable and the share of calories produced via rain-fed agriculture (Share_rainfed) and governance as independent variables (Model 10, table S1). The independent variables Share_rainfed and governance are consistently significant across all of the tested models (table S1). Further, the model demonstrates the lowest AIC ($-176.2$) among all the models considered. Lastly, we examined the $R^2$-value of the model, which demonstrates that the model can describe 74% of the between-country variation in the SIDI, which is among the highest values reported (table S1). The final model is established as:

$$\text{SIDI} = \beta_0 + \beta_1 \text{Share}_\text{rainfed} + \beta_2 \text{Governance} + \epsilon \quad (4)$$

where $\beta_0$ is the intercept, $\beta_1$ is the coefficient estimate for the share of rainfed calories in the total production and $\beta_2$ is the coefficient estimate for governance and $\epsilon$ is the robust standard error. Coefficient estimates derived from the model are then applied to the projections of the independent variables that already exist in the SSP framework. Share of rain-fed agriculture (Share_rainfed) was updated every five years, as it evolves along with the number of calories produced via sustainable irrigation (section 3 in the SM). We report a 95% confidence interval for our projections. Establishing a statistical link between those variables and the SIDI then provides the sufficient basis to allow consistent 21st century projections of the SIDI alongside different scenarios.

### 3. Results

We project the SIDI in the 21st century to make a first attempt at comprehending to what extent socioeconomic factors could constrain sustainable irrigation deployment and thus impede YGC by relieving water limitations. First, we assess the SIDI in year 2000 globally and for the World Bank regions, which was determined using estimates of calories produced in that year (section 3.1, Rosa et al 2018). After, we examine the regional and global development of the SIDI, with projections starting in 2020 and ending in 2100 (section 3.2, figure 2(a)). To compare the results across the regions, figure 2(b) displays the regional projections for a Middle of the Road scenario (SSP2). Finally, we consider the people that could potentially be fed with the additional calories produced via sustainable irrigation (section 3.3, table 1) and assess to what extent the yield gap could be closed in the most optimistic scenario (SSP1) (section 3.4, table 2).

#### 3.1. Sustainable irrigation deployment in 2000

The global average SIDI for the year 2000 indicates that only 23% of the global sustainable irrigation potential was being used at the beginning of the century (figure 2(a)). The SIDI in 2000 varies largely across countries and regions (between 0.05 and 0.40) (figures 1 and 2). Countries scoring a low SIDI in 2000 are either not availing a vast percentage of the biophysical potential to sustainably irrigate or are currently mainly irrigating unsustainably. South Asia has the highest SIDI in 2000, followed by East Asia & Pacific—both displaying results above 0.40. This indicates that, compared to other regions, these regions are currently using a high fraction of their sustainable irrigation potential and therefore the ability to buffer precipitation variations via irrigation endows them with a relatively high adaptive capacity in the agricultural sector (figure 2(a)). Countries in South Asia, such as India or Pakistan, are known for their dependence on the agricultural sector and have a long history of large-scale irrigation implementation (Anik et al 2017), although this has led some of them to currently rely on unsustainable exploitation of water resources (Rosa et al 2018). 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 (less than 1%). 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.

#### 3.2. Projecting sustainable irrigation deployment in the 21st century

The projections of the SIDI alongside the five SSPs display large heterogeneities between regions and scenarios. Overall, SSP5 and SSP1 are the most optimistic scenarios, which is consistent with the scenario storylines as governance reaches the highest levels in these scenarios (figure 2(a)). SSP3, also in line with the storylines, is the most pessimistic scenario, displaying the smallest improvements for the SIDI. The global SIDI is projected to improve from 0.23 to 0.53 (0.48–0.58) by the end of the century in a Sustainability scenario (SSP1)—which is an improvement by more than 130%. In contrast, in a Regional Rivalry scenario (SSP3), the SIDI would only improve to 0.43 (0.39–0.47) (an 87% improvement). South Asia is the region closest to narrowing the yield gap by relieving water limitations by the end of the century,
Figure 2. Projections of the Sustainable Irrigation Deployment Index. (a) Trajectories are shown for the whole globe and the World Bank regions, and for the different SSP-scenarios. (b) Regional projections of the SIDI for Middle of the Road scenario (SSP2). The data for 2000 is from Rosa et al (2018) and the projections are shown from 2020 until 2100 (shaded areas report the 95% confidence interval for the projected values). The regional projections are displayed for the World Bank regions (World Bank Group) (delineation of the regions can be seen in figure 3).

Table 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 SSP. Total people fed was quantified assuming a calorie intake of 3343 kcal per capita per day assuming a 20% animal-based diet (Rosa et al 2018). Population projections are for each SSP in the year 2100 from Samir and Lutz (2017). 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     | 1.73 (1.57–1.88)     | 2.10 (1.93–2.28)     | 2.30 (2.10–2.51)     | 6.88                                | 33% (30–36)   |
| SSP2     | 1.71 (1.55–1.87)     | 2.02 (1.85–2.19)     | 2.18 (2.00–2.37)     | 9.00                                | 24% (22–26)   |
| SSP3     | 1.69 (1.53–1.84)     | 1.91 (1.75–2.07)     | 1.96 (1.80–2.13)     | 12.6                                | 15% (14–16)   |
| SSP4     | 1.70 (1.55–1.86)     | 1.98 (1.82–2.15)     | 2.15 (1.92–2.27)     | 9.27                                | 23% (20–24)   |
| SSP5     | 1.72 (1.57–1.88)     | 2.09 (1.91–2.26)     | 2.31 (2.10–2.51)     | 7.36                                | 31% (28–34)   |
reaching an index of 0.78 (0.71–0.84) in SSP1, compared to only 0.68 (0.62–0.73) in SSP3. Sub-Saharan Africa could reach a SIDI of 0.50 (0.46–0.55) by 2100 in a Sustainability scenario, a > 550% improvement compared to 2000 levels. In contrast, in SSP3, the SIDI in Sub-Saharan Africa would not go above 0.35 (0.32–0.38). As can be seen in figure 2(b) (red line), Sub-Saharan Africa could reach higher SIDI levels than Europe and North America by the end of the century in a Middle of the Road-scenario (SSP2). Our model projects an increase in sustainable irrigation between 2000 and 2020 for all regions. This increase is in accordance with the global annual quantity of water withdrawn for irrigation purposes in the same time period, for which an increase of 6% between 2000 and 2020 has been recorded for the available countries (table S3) (FAO 2022). The FAO of the United Nations further reports that irrigated areas have increased by 52 million hectares between 2000 and 2019 (FAO 2022).

Countries with already high levels of governance (e.g. Europe) in the baseline period (2000) will only be able to further improve the SIDI to a limited extent and in line with the assumptions embedded in the SSPs. They also do not indicate a stark difference between the scenarios (see confidence intervals in figure 2(a) for North America and Europe). By contrast, countries with low levels of governance (e.g. Sub-Saharan Africa) in the baseline period (2000), have more room for improvement and thus can enhance the SIDI to a greater extent, which also makes the differences between scenarios more significant.

3.3. 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 (section 2 in the SM). Figure 3(a) shows the total sum of people fed via sustainable irrigation in 2020, 2050 and 2100 per region under a Sustainability scenario (SSP1). Figure 3(b) shows the average percentage increase in people fed via sustainable irrigation per region from 2020 to 2100 in the 21st century for the different SSP scenarios.

According to our model estimates, East Asia & Pacific and South Asia are the regions currently producing the highest number of calories via sustainable irrigation in 2020 by feeding 799 (738–859) and 450 (416–485) million people, respectively. The lowest calorie production and number of people fed through sustainable irrigation is estimated for Sub-Saharan Africa and Middle East & North Africa (39 (33–46) million and 57 (52–67) million, respectively) (figure 3(a)). The analysis shows that the regions in which a lower amount of people are fed via sustainable irrigation in 2020 could be able to make the greatest improvements by 2100 in that regard. Sub-Saharan Africa, for example, could experience the highest average percentage increase in people fed via sustainable irrigation, by more than 300% until 2100 (compared to 2020) in a Sustainability scenario. This would increase the total amount of people being fed via sustainable irrigation from 39 million people in 2020–111 million people by the end of the century (figure 3). In contrast, East Asia & Pacific, the region with the highest amount of people being fed via sustainable irrigation in 2020, would see this amount increase by only around 20% until 2100 in SSP1 (from 799 million in 2020–955 million people in 2100), hereby constituting the highest calorie production via sustainable irrigation in our analysis. Differences between the socioeconomic scenarios are less pronounced in regions with a smaller relative increase in the SIDI (e.g. a 6% difference between SSP1 and SSP3 in North America as opposed to 46% difference in Sub-Saharan Africa in 2100) (figure 3(b)).

Globally, we find that in SSP1, sustainable irrigation could feed a total of 2.3 (2.1–2.5) billion people by the end of the century (table 1)—this represents 33% of the projected global population for this scenario (Samir and Lutz 2017). In contrast, only 1.96 (1.80–2.13) billion people could be fed via sustainable irrigation by the end of the century in a SSP3 scenario (15% of the global population). The analysis shows that SSP1 and SSP5 will have the best chances of meeting projected global food demands, whereas SSP3 and SSP4 will face the highest challenges in reaching that objective (table 1).

3.4. YGC

According to the estimates from Rosa et al (2018), relieving water limitation for crop production would mean that a total of 4 billion people could be fed via sustainable irrigation under current climate conditions (table S2). However, these estimates did not consider socioeconomic constraints to irrigation deployment. Our results show that accounting for

| Region                  | People fed in 2100 (millions) | Remaining yield gap |
|-------------------------|-------------------------------|---------------------|
| East Asia & Pacific     | 955 (877–1032)                | 40% (35–46)         |
| South Asia              | 523 (481–565)                 | 22% (16–29)         |
| Europe                  | 173 (153–193)                 | 62% (56–67)         |
| Central Asia            | 222 (203–242)                 | 43% (39–49)         |
| Latin America & Caribbean | 156 (140–172)              | 43% (38–48)         |
| North America           | 91 (78–104)                   | 69% (64–75)         |
| Middle East & North Africa | 74 (68–80)                 | 40% (35–45)         |
| Sub-Saharan Africa      | 111 (102–121)                 | 50% (45–54)         |
| Africa                  | 2305 (2102–2509)              | 51% (46–55)         |

Table 2. Total amount of people fed per region (reported in million per year) via sustainable irrigation in 2100 for SSP1 and the remaining yield gap for the World Bank regions (percentage difference between projected sustainable irrigation calories produced in 2100 for a SSP1 scenario and sustainable irrigation calories produced in a YGC-scenario from Rosa et al (2018)). The numbers in brackets report the 95% confidence interval.
them would substantially constrain this potential. We indeed find that by the end of the century, even in the most optimistic scenario (SSP1), only about half of the biophysical potential would be realized (around 2 billion people compared to the estimated 4 billion). This underlines a growing need to incorporate socioeconomic projections into analyses of future food security (Beltran-Pea et al. 2020).

Table 2 shows the remaining yield gap in 2100 for a SSP1 scenario. The remaining yield gap describes the percentage difference between the yield projected for 2100 and the maximum attainable yields. This means for example that Europe is 63% away from the maximum attainable yields by the end of the century in a SSP1 scenario (table 2). According to this scenario South Asia would be able to use 78% of the YGC potential by 2100, followed by the Middle East & North Africa (60%) and East Asia & Pacific (60%). Table 2 also 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 region with the highest number of people fed (955 million), we find South Asia (523 million) and Central Asia (222 million people) to be countries with high sustainably irrigated calorie production 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 (111 million) than North America (91 million) and Middle East & North Africa (74 million). This would still be less than in Europe where the number of people fed via sustainable irrigation would be comparably high (173 million) while the yield gap would remain substantial (62%). These differing figures reflect the effect of the already high levels of governance and low levels of sustainable irrigation deployment (in comparison to the biophysical potential) in Europe and North America in 2000, which restricts further deployment of sustainable irrigation in our analysis. 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.

### 4. Discussion

Sustainable irrigation is one of the main adaptation responses in the agricultural sector with regards to climate change and population growth (Rosa et al 2020b, Droppers et al 2021). We find that there is a wide gap between the biophysical potential for sustainable irrigation and the actual implementation of sustainable irrigation. Globally, less than one third of the biophysical global sustainable irrigation potential was exploited by 2100, followed by the Middle East & North Africa (60%) and East Asia & Pacific (60%).

Table 2 also 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 region with the highest number of people fed (955 million), we find South Asia (523 million) and Central Asia (222 million people) to be countries with high sustainably irrigated calorie production 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 (111 million) than North America (91 million) and Middle East & North Africa (74 million). This would still be less than in Europe where the number of people fed via sustainable irrigation would be comparably high (173 million) while the yield gap would remain substantial (62%). These differing figures reflect the effect of the already high levels of governance and low levels of sustainable irrigation deployment (in comparison to the biophysical potential) in Europe and North America in 2000, which restricts further deployment of sustainable irrigation in our analysis. 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.
total crop production to be a factor with significant explanatory power.

4.1. Governance as an indicator of sustainable irrigation expansion
Among our socio-economic factors considered, the indicator of governance (Kaufmann 2010) shows the most significant relationship with the SIDI (table S1). This suggests that countries with better institutions, less corruption and better regulatory quality (to name a few characteristics of what constitutes ‘good governance’ according to the indicator used here (Andrijevic et al 2019)) are also closer to their maximum sustainable crop yields.

Poor governance has been identified as a key constraint to adaptation globally (Berrang-Ford et al 2019, Thomas et al 2021). Institutional capacity is a major factor in determining a country’s access to funding (Garschagen and Doshi 2022), which is relevant for sustainable irrigation expansion. The level of corruption in a country has been shown as particularly relevant (Lesnikowski et al 2015), because it weakens institutions, the public trust and investments which can lead to a misuse of funds intended for adaptation implementation, such as implementing sustainable irrigation (Mahmud and Prowse 2012).

While we do not attempting to draw a causal relationship between governance and sustainable irrigation, we note that this is in line with previous findings that have identified governance as a main factor currently constraining sustainable irrigation deployment across the globe (e.g. Levidow et al 2014, Higginbottom et al 2021). For example, the lack of adequate assistance to develop and adopt better approaches for environmental sustainability, while also maintaining their financial and social objectives, was identified a major obstacle towards sustainable irrigation implementation in Europe (Levidow et al 2014). In Sub-Saharan Africa, the implementation of large-scale irrigation systems, despite financial means being available, were hindered by governance related factors such as ineffective national bureaucracies (Higginbottom et al 2021). Even though irrigation has long been emphasized a solution to intensify agricultural production, support rural economic development and enhance resilience to climate variability and change (Lefol et al 2019, Higginbottom et al 2021), most Sub-Saharan countries do not yet have the possibility to access water management technologies and benefit from it, a phenomenon denominated economic water scarcity (Rosa et al 2020a). Reforming management practices are a solution to improve the performance of sustainable irrigation within the region (Higginbottom et al 2021).

4.2. Projections over the 21st century
Our projections along SSPs offer the perspective to improve climate impact assessments within the modeling community, which currently do not include a component of adaptive capacity in the agricultural sector. There are many differences between the scenarios and regions. We find that SSP1 and SSP5 reach the highest level of sustainable irrigation expansion by the end of the century in all the regions. This is mainly because good governance will be reached in almost all countries in SSP1 and SSP5 (Andrijevic et al, 2020). On a regional level we see that countries with currently low levels of governance can improve the most. The projections of the SIDI overall emphasize the vast potential for improvement in the regions with currently low levels of socioeconomic development (e.g. Sub-Saharan Africa) and the limited advancement in regions with currently high levels of socioeconomic development (e.g. Europe). It is important to highlight that this is does not mean that sustainable irrigation might not advance in Europe, but rather that according to our methodological framework, Europe would already have the socioeconomic capabilities to deploy sustainable irrigation towards YGC today. Factors hindering implementation are not represented in our global capability-based approach.

To the contrary, very low levels of governance to date represent a key constraint to adaptation action in many developing countries, and in particular Sub-Saharan Africa (Thomas et al 2021). Overcoming those constraints will be critical to enable successful adaptation, especially in regions where increasing climate change and population growth will put further pressures on the agricultural sector. Our results indicate the potential for doing so. By translating our projections of the SIDI into people fed (section 3.3) we find that in the most optimistic scenario (SSP1), 33% of the world population could be fed via sustainable irrigation expansion by the end of the century. It shows that other measures (e.g. crop migration) need to be implemented to sufficiently counteract current trends of warming and population growth. This is the first time estimates of sustainable irrigation expansion and people fed account for socioeconomic constraints. The importance of including socioeconomic constraints becomes ever more visible when looking at the remaining yield gap in 2100 (section 3.4). Compared to the suggestions of previous estimates, the extent to which the yield gap can be closed depends as much on socioeconomic constraints as it does on biophysical limits.

4.3. Sustainable irrigation and climate change
It is certain that future calorie production and the sustainable irrigation expansion potential will be impacted by climate change through its alteration of precipitation amounts and timing, the occurrence of extreme events (Tabari 2020), as well as changing soil moisture and crop water requirements (Rosa et al 2020b). 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 (Schleussner et al 2016, Byers et al 2018). However, in order to comprehend and isolate the socioeconomic drivers of sustainable irrigation expansion, to reduce further uncertainty related to projected climate impacts and to stay consistent with the design of the SSP framework, we refrain from additionally including the effects of climate change on water availability and demand for irrigation in this study (Elliott et al 2014, O’Neill et al 2017, Rosa et al 2020b). The SIDI and future estimates of sustainable irrigation potential were derived using present-day crop water requirements and surface water availability quantities (for more information see Rosa et al 2018). Since our scenarios do not account for the potential impacts of climate change, future research should aim at conflationing the potential impacts of climate change on sustainable irrigation expansion with considerations of future socioeconomic development.

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 modeling efforts (Wang et al 2021), socioeconomic considerations limiting irrigation deployment are so far not consistently implemented. To include socioeconomic constraints to sustainable irrigation expansion, the level of sustainable irrigation assumed in current modeling efforts could be constrained by our estimates of the SIDI, by translating the SIDI into a fraction of irrigation that can be deployed (average over the country and adjusted to the spatial scale, e.g. grid level). Our projections also provide entry-points to include information on the future climate resilience and adaptive capacity in IAMs.

4.4. Limitations

Developing quantified trajectories for sustainable irrigation expansion in line with socioeconomic scenarios in the 21st century comes with a range of limitations. One major constraint is the limited data availability in relation to irrigation water withdrawals and its implications for the water system. Reliable estimates of irrigation water withdrawals that allow for a more informed management of global freshwater resources are scarce (Puy et al 2021). To establish projections for sustainable irrigation expansion we needed to identify the gap between the current level of sustainable irrigation and the optimum level of sustainable irrigation. Therefore, we use the dataset provided by Rosa et al (2018), as it is to our knowledge the only global dataset that provides information on observed and intensified crop production via irrigation and differentiates between sustainable and unsustainable use of water. This dataset, which is quantified using a process-based crop water model, is only available for two instances: the year 2000 and a YGC scenario. While it would have been more comprehensive to include time series in the statistical analysis, no monitored information on the development of sustainable irrigation is available.

The projected socioeconomic developments within the SSPs are hypothetical scenarios, quantified global narratives of development. The presented scenarios of sustainable irrigation expansion are consistent with the scenario narratives but do not predict or forecast actual futures. Further, in order to allow for an internally-consistent temporal extension of the SIDI within the SSP framework, we establish a statistical relationship between the quantified variables from the SSPs and the SIDI. Due to the limited number of quantified variables from the SSPs, we are not able to include all factors that could be relevant for sustainable irrigation expansion. For example, the level of environmental concern, which plays a relevant role in the original storylines of the scenarios (O’Neill et al 2017), could be a meaningful variable to consider if sufficient data were available. The statistical relationships we present in this study do not mean to assess causalities in detail and especially do not imply that good governance is the only driver of sustainable irrigation expansion; they rather constitute a practical approach to derive the projections for the 21st century presented in this study. The projections also do not reflect actual implementation of irrigation, but rather the capabilities of societies to do so.

Moreover, other factors such as trade or dietary change were not considered, even though they will further influence the amount of people being fed in the future. For example, trade has been increasingly important for food security and rising populations in the Global South, especially in countries with limited biophysical resources (D’Odorico et al 2019, Bren D’Amour et al 2020). The data used to establish the SIDI does also not distinguish between different irrigation systems, rather, it assumes that the most widely used surface irrigation is implemented. Replacing surface irrigation systems by sprinkler or drip irrigation could reduce non-beneficial consumption of irrigation water by 54% and 76% (global average), respectively (Jägermeyr et al 2015). While some questions around irrigation efficiency remain (Grafton et al 2018), diversifying irrigation systems could further enhance the potential for sustainable irrigation expansion and global crop production.

5. Conclusion

By introducing the SIDI, we assess how socioeconomic conditions are related to the current level of sustainable irrigation with respect to its potential under a YGC 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 capacity (Higgiebottom et al. 2021). The two identified predictors, namely the level of governance and the share of rainfed agriculture, explain more than 74% in the current across-country variations in utilized sustainable irrigation potential across the globe. Basing on this comprehension of which factors currently explain sustainable irrigation deployment, we project the evolution of sustainable irrigation deployment throughout the 21st century alongside the socioeconomic development of countries. Socioeconomic constraints that we can link to low levels of 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.

It is also in those regions where most of the population growth over the 21st century is expected to occur. Increasing levels of adaptive capacity in the agricultural sector will therefore be crucial 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 2050 (Graves et al. 2019). 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 productivity (Rosa et al. 2020a).

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 century (Myers et al. 2017). 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 agenda (Steirimikis and Baležentis 2020).

Data availability statement

The data that supports the findings of this study are available via the following link (https://github.com/nicolenicolen/Sustainable_irrigation_2021).

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Conflict of interest

The authors declare no competing interests.

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