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PAPER

Solar irrigation potential in Sub-Saharan Africa: a crop-specific techno-economic analysis

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Abstract

In this study, we introduce an integrated modeling framework that combines a hydrologic model, a biophysical crop model, and a techno-economic model to assess solar irrigation potential in Sub-Saharan Africa (SSA) based on seven commonly grown food crops-maize, wheat, sorghum, potato, cassava, tomato, and onion. The study involves determining the irrigation requirements, location-specific capital investment costs, crop-specific profitability, and the cropland area under various cost scenarios (low and high) and soil fertility (low, moderate, near-optimal, and optimal) scenarios. Our research reveals considerable potential for solar irrigation, with profitability and viable cropland areas that vary according to crop type, irrigation system cost scenarios, and soil fertility levels. Our assessment shows that approximately 9.34 million ha of SSA's current rainfed cropland are hydrologically and economically feasible for solar irrigation. Specifically, maize and onion display the lowest and highest viability, spanning 1–4 million ha and 29–33 million ha, respectively, under optimal soil fertility conditions. In terms of profitability, maize and onion rank as the least and most economically viable crops for solar irrigation, yielding average annual returns of $50-$125/ha and $933-$1450/ha, respectively, under optimal soil fertility conditions. The lower and upper bounds of profitability and cropland range correspond to high-cost and low-cost scenarios, respectively. Furthermore, our study reveals distinct regional differences in the economic feasibility of solar irrigation. Eastern Africa is more economically favorable for maize, sorghum, tomato, and cassava. Central Africa stands out for onion cultivation, whereas West and Southern Africa are more profitable for potato and wheat, respectively. To realize the irrigation benefits highlighted, an energy input of 940-2,168 kWh/ha/yr is necessary, varying by crop and geographic sub-region of the SSA sub-continent. Our model and its results highlights the importance of selecting the right crops, applying fertilizers at the appropriate rates, and considering regional factors to maximize the benefits of solar irrigation in SSA. These insights are crucial for strategic planning and investment in the region's agricultural sector.

1. Introduction

Sub-Saharan Africa (SSA) is currently the most food-insecure region in the world, with a high dependence on food imports to plug demand deficits [1]. Over 69% of the region's food is produced by smallholders who account for 80% of the farmlands that are responsible for 90% of the region's food output [2–4]. This is despite their reliance on traditional farming methods characterized by low mechanization [1], minimal fertilizer usage [5], and high dependence on natural rainfall–only about 5% of the region's arable land was under irrigation as of 2010 [6])– leading to huge yield gaps [7]. On the other hand, the SSA region's annual population growth rate -approximated at 2.4% [8]-is the steepest in the world. This combination of agricultural under-performance and a high population growth rate threatens to exacerbate the current food insecurity problem, undermine the region's effort to alleviate poverty [1] and destabilize its socioeconomic systems [1, 9]. A study by the Food and Agricultural Organisation (FAO) of the United Nations (UN) projected a 60% increase in food production (with 2006/2007 as the base year) for the world to feed its growing population in year 2050 [10]. Production pressure is even higher for SSA sub-continent considering that the region's population is projected to exceed 2 billion by 2050 [11], which is more than twice the population of the base year (2020). The projected climate-induced rainfall variability threatens the region's already under-performing agricultural sector [9, 12, 13], calling for the need to re-appraise the current food production practices in order to improve productivity and enhance adaptation.

One of the measures with potential to close the current agricultural yield gaps is irrigation [7, 13–17]. Studies have shown that irrigation can potentially double the productivity of field crops [16] by facilitating additional cropping seasons, and enabling farming of high-value crops that require more consistent water supplies [14, 18]. Moreover, irrigation serves as a safeguard against climate-induced droughts, a threat projected to intensify in the future [12, 15]. However, despite its promising potential and demonstrated success in other developing regions of the world, like South Asia [19, 20] and the Middle East and North Africa (MENA) [21], irrigation adoption in SSA has been slow due to region-specific barriers including high capital costs beyond smallholder farmers' affordability [22, 23], inadequate market linkages [24, 25], nascent policies and regulatory frameworks [25, 26], and limited access to affordable irrigation energy. On average, irrigation energy costs can account for up to 33% of irrigation crop production costs [27], emphasizing the importance of affordable energy in reducing overall irrigation farming expenses. As of 2022, only about 45% of SSA's population had access to electricity [28], primarily concentrated in urban areas, while agriculture is predominantly a rural activity. In the absence of reliable grid power, diesel engines and solar photovoltaic (PV) systems have emerged as alternative sources of motive power for irrigation. Solar PV-powered irrigation-henceforth solar irrigation- has demonstrated viability in rural areas with high diesel fuel costs [29, 30], offering promise in enhancing food security and alleviating rural poverty, particularly among smallholder farmers [31]. Nevertheless, the aforementioned barriers significantly impede its wider adoption, underscoring the necessity for research to inform evidence-based policy interventions. Some of the needed studies include spatial and economic assessments to delineate profitable locations for solar irrigation across the SSA region for each important food crop. Such insights are crucial for decision-making processes aimed at maximizing the benefits of irrigation by identifying suitable locations and crops for irrigation investment.

The current literature includes studies on irrigation potential in SSA, examined at both country-level [32–35] and continental scales [36–39]. These range from geographic information system (GIS)-based environmental suitability assessments [32, 33] to identify viable locations for solar irrigation, to comprehensive integrated modeling, combining GIS-environmental suitability, hydrological, crop simulation, and economic benefits-costs analyses [34, 35, 37, 40, 41]. However, only a limited number of these previous studies have considered solar irrigation potential including assessing and delineating suitable cropland locations for solar irrigation [32, 33] and economic benefits thereof [36, 40, 41]. For example, Xie *et al* [36] perform a comparative analysis of solar versus diesel-powered irrigation and spatially delineate cropland clusters (at 1 km resolution) where solar is more cost-effective over diesel-powered irrigation. Meanwhile, Wamalwa *et al*'s [40] study on the economic feasibility of solar irrigation in Kenya highlight the critical roles of crop type and groundwater depth on its feasibility. Their findings underscore that horticultural crops are generally more economically profitable compared to cereals and tubers. In a more recent study, Falchetta *et al* [41] present one of the most comprehensive assessment of the economic feasibility and nutritional impacts of solar irrigation in SSA. Their study also assessed the implications of climate change on solar irrigation potential and the electricity access implications from excess solar PV system capacity. However, Falchetta *et al*'s study [41], does not provide a detailed crop-specific irrigation viability analyses, particularly lacking is the precise delineation of profitable irrigable areas for the 19 crops considered in the study. This omission highlights the need for further studies to explicitly delineate the current cropland clusters that are viable for solar irrigation of each of the important food crops grown in SSA. The output of such a study would be helpful to local farmers, rural development agencies, and policy makers, among others, in making informed decisions about solar irrigation potential in SSA. By *viable locations*, we refer to cropland clusters that are both hydrologically and techno-economically feasible to solar-irrigate.

In this study, we present a crop-specific scenario assessment of the economic feasibility of solar irrigation, focusing on seven food crops commonly grown in SSA (viz: maize, wheat, sorghum, cassava, potato, onion, and tomato), employing various assumptions. By *crop-specific scenario assessment*, we mean an independent evaluation of solar irrigation feasibility for each of the seven crops, aiming to identify opportunities for crop substitution that can maximize irrigation benefits. The choice of the crops considered in this study is based on their economic and nutritional importance in the SSA region. Maize, wheat, and sorghum are the primary cereals cultivated in the region, whereas cassava and potato are the prevalent tuber crops. Onion and tomato are grown as horticultural crops, serving both as food and a source of income. Together, these seven crops occupy 50 (approximately 84 out of 168 million hectares) of the cropland allocated for food production in SSA. The distribution of this cropland by crop type is detailed in figure SI 3 in the supplement. Moreover, Maize, along with cassava, wheat, rice, and palm oils-though the latter two are not included in this study-contribute up to 54% of the daily caloric intake in the region [42]. As a principal staple, maize is cultivated on over 27 million hectares within SSA and represents 19.7% of the daily caloric consumption in Eastern and Southern Africa [43]. Wheat and cassava contribute 8.3% and 10.5%, respectively, to the daily per capita calorie consumption [42].

Our study aim is to delineate locations–spatially and economically—where it is viable to solar-irrigate each of the seven crops, including their associated profitability. We argue in this study that certain crops currently grown on the SSA's largely rainfed cropland may not optimally contribute to alleviating the region's economic poverty and the current food insecurity. Therefore, given the options, farmers might benefit from rationally and strategically switching crops to maximize irrigation benefits. Many farmers in SSA face challenges in accessing farm inputs, particularly fertilizers, due to their high costs. It is estimated that 10% of farmers in SSA grow crops without any artificial fertilizer application and half of those who use fertilizers depend on low-value organic options, which contribute to sub-optimal crop yields [44]. To account for these disparities in fertilizer use rates in our model, we incorporate a scenario-based sensitivity analysis of soil fertility. The primary research questions addressed in this study are: (i) Where in the current rainfed cropland of SSA is it feasible to solar-irrigate commonly cultivated food crops?; (ii) What is the profitability of solar irrigating commonly cultivated crops in SSA's rainfed cropland?; (iii) What area of SSA's rainfed cropland is viable for solar irrigation of the region's commonly grown food crops?; and (iv) What is the impact of fertilizer application rates on irrigation feasibility in SSA? In addressing these questions, our study makes several contributions to the existing literature: (a) development of a detailed hydrological and techno-economic framework for assessing solar irrigation feasibility in SSA based on attainable yield simulations by a biophysical crop model; (b) evaluation and quantification of the annual irrigation profitability of each crop, delineating geographic areas where solar irrigation is viable; and (c) assessment and quantification of the impacts of fertilizer application rates on irrigation feasibility in SSA.

The remainder of this paper is organized as follows: section 2 presents the methods, including the modeling framework, data sources, key model assumptions, and economic model formulation; section 4 presents the study's results; section 5 discusses the results and provides recommendations; while section 6 concludes the paper.

2. Model, data and methods

In this section, we present the methods, modeling framework, data sources, and assumptions underpinning the proposed study. The methods include techniques for estimating crop yield gains due to irrigation, assessing land suitability for irrigation based on groundwater recharge, and evaluating the technical and economic feasibility of solar irrigation across the 10 km gridded pixels of SSA's rainfed cropland.

2.1. The modeling framework and data inputs

Figure 1 shows the schematic layout of our modeling framework. As shown, the model comprises of four modules: (i) the crop module for estimating the irrigation water requirement (W_{irr}); (ii) the pump module for estimating the irrigation energy demand (E_{irr}) with groundwater depth and W_{irr} as inputs; (iii) the solar pump sizing module for sizing the solar irrigation system based on the peak daily E_{irr} and site-specific solar radiation data; and (iv) the economic module for estimating the metric of interest, which in this case is the NPV of irrigation. The irrigation module in figure 1 is a simplified model based on the FAO's Penman–Monteith equation [45]; a detailed account is given in section SI 1 in the supplement. For irrigation yield gain, we rely on attainable yield simulated from the FAO's Aquacrop model [46]; A detailed account on AquaCrop model simulation and irrigation yield gain results is available in section SI 3 of the supplement. Comprehensive modeling, including crop file calibrations and the setup of simulation projects, is based on the methods developed by Izar-Tenorio *et al* [47].

The main datasets used in our study include (i) the current rainfed cropland data of SSA; (ii) crop producer (farm-gate) prices; and (iii) irrigation infrastructure costs. The first dataset–rainfed cropland–is obtained from the International Food Policy Research Institute's (IFPRI's) SPAM2017 v2.1 data product for the SSA region [48]. In this study, we have limited our analysis to the current rainfed cropland by assuming that it (rainfed cropland) meets arability conditions. We have excluded the current irrigated cropland based on the assumption that it is already economically viable to irrigate there. For crop prices, we rely on producer prices from Food and Agricultural Organisation Statistics (FAOSTAT) [49]. We also use the FAOSTAT

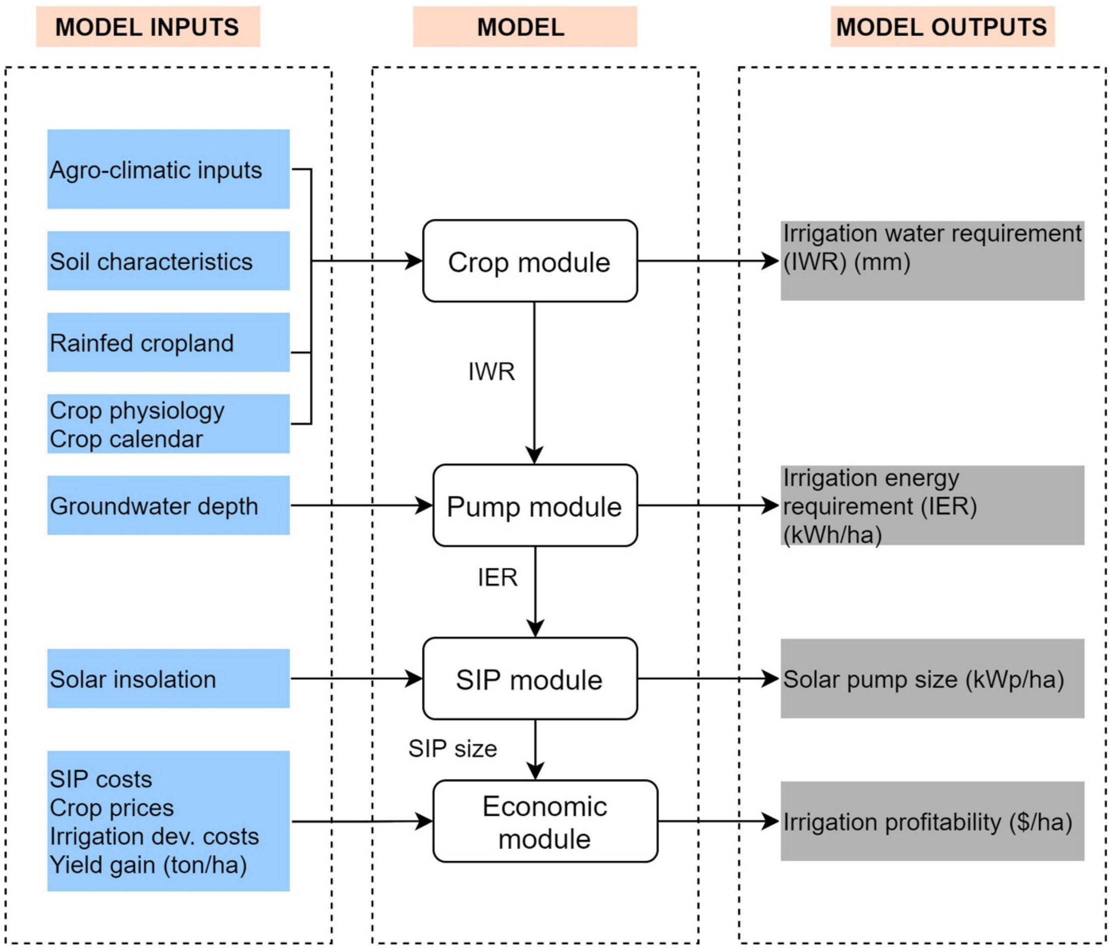


Figure 1. Schematic layout of the model and the modeling process. Agro-climatic inputs include wind speed, solar irradiation, precipitation, and temperature (min, mean max). SIP = solar irrigation pump.

national yield averages to validate the yield estimates from crop simulation model; a detailed account on irrigation yield validation is given in section SI 3.1 in the supplement. The available country-level crop prices for the SSA region are fragmented with missing values. Some countries do not have continuous data for the period of interest (from 2001 to 2020) for the crops considered in this paper. To address the data gaps' issue, we impute missing values with sub-regional averages. We use annual producer prices at the country level as representative prices in each cropland cluster (10 km gridded cells) within a given country. In the same vein, we use country-level costs–imputed with regional averages–for borehole drilling and development costs obtained from previous studies [27, 50]. We acknowledge limitations of these course cost estimates occasioned by data scarcity, necessitating the need for cost-centered sensitivity analysis of the results obtained from the model.

For solar irrigation system costs, we rely on the break-even cost of solar PV over diesel-powered irrigation, drawing from the work of Xie *et al* [36],thus excluding cropland clusters where diesel-powered irrigation is cost-competitive, as in Falchetta *et al* [41]. For discount rates, we adopt the country-level weighted average cost of capital (WACC) for solar home systems (SHSs) in Agutu *et al* [51]. This choice is predicated on the comparable deployment scales of SHSs and solar irrigation systems, particularly for smallholder applications, and our analysis focus on solar irrigation feasibility at the 1-hectare level.

2.2. General model assumptions

In this sub-section, we outline the fundamental assumptions that form the basis of our model and the modeling process.

Firstly, although various crops are cultivated on the current rainfed croplands of SSA, our study focuses exclusively on the seven commonly cultivated food crops in the region: maize, wheat, sorghum, potato, cassava, tomato, and onion. While multiple crops could potentially be grown simultaneously on each of the 10 km gridded cropland clusters (spatial analysis resolution considered in this paper), our assessment independently evaluates the performance of each of the seven crops. This approach allows us to compare

Table 1. Criteria and input data used in formulating cropland inclusion constraints.

Data category	inclusion criteria	Data source
Groundwater yield	$>0.1 \mathrm{l\,s^{-1}}$	British Geological Survey [52]
Daily solar insolation	$>0.5 \mathrm{~kWh\,m^{-2}}$	WorldClim [59]
Irrigation yield gain	>0	From model simulation
Groundwater recharge	>0	British Geological Survey (BGS) [60]

their economic potential for solar irrigation, providing valuable insights for determining the most economically viable crops to cultivate in each gridded cropland cluster.

Secondly, concerning irrigation water sources, our analysis is confined to groundwater, despite the economic viability of surface irrigation where accessible. This delimitation is made to simplify the modeling complexity associated with costing irrigation water conveyance systems. The costing of such systems involves intricate considerations of sizing and routing water lines, which cannot be accurately estimated without ground-truth data on cropland demarcations and routing constraints. Additionally, we restrict our analysis to groundwater due to its natural abundance in Africa and its ease of access [52]. Groundwater can be accessed virtually from anywhere that is technically and economically feasible to drill and develop, reducing the costs associated with extensive water reticulation systems [53]. On irrigation infrastructure costs, we assume 10 ha of cropland per groundwater well, following precedents in literature [27, 54]. We scale the drilling and development costs of a borehole to a hectare level.

The third assumption pertains to the study's inclusion criteria for cropland clusters. Table 1 outlines a select set of technical and environmental constraints considered in our model, restricting our analysis to locations that are hydrologically and technically feasible for solar irrigation. For example, we exclude all cropland cells within agro-ecological zones with insufficient groundwater recharge to mitigate environmental concerns related to over-pumping; See section 2.4 for the recharge model development.

The fourth assumption pertains to the choice of irrigation technologies. Although various irrigation systems, including gravity-fed, manual, and pressurized systems (such as sprinkler and drip), are practiced in SSA, our analysis in this paper is limited to the latter systems due to their high irrigation water application efficiencies from a sustainability standpoint. Both sprinkler and drip irrigation can be applied to the common row crops considered in this study, with differences in efficiencies, head requirements, and costs [55]. Drip irrigation is the most efficient (up to 85%) compared to sprinkler irrigation (up to 70%) [55]. We adopt sprinkler irrigation for dense cropping cultivation (common for cereal crops like maize, wheat, and sorghum) and tuber crops (potato and cassava). Drip irrigation is selected for high-value horticultural crops–onions and tomatoes in this case–due to their high vulnerability to fungal and bacterial diseases when water is logged on their leaves [56]. In addition to irrigation efficiencies, our model also considers crop water withdrawal efficiencies as detailed in [27, 41]; the applicable values are provided in table SI 1 in the supplement.

Lastly, in calculating the net present value (NPV) of irrigation-a profitability metric in this paper-we assume a 15% income loss for the farmer in post-harvest crop handling, consistent with established studies [57, 58].

2.3. Irrigation energy requirement

The irrigation water requirement, W_{irr}, is typically estimated based on crop evapotranspiration, which is the combined water loss due to transpiration and evaporation from plant and soil surfaces. This lost water must be supplied through either natural precipitation or artificial irrigation to facilitate effective crop growth. In this study, we develop a simplified model to estimate crop W_{irr}, from which the groundwater-fed irrigation energy requirement, E_{irr}, is derived. A brief explanation is provided here, with a detailed account in section SI 1 of the supplement. The daily E_{irr} for groundwater-fed irrigation is a function of the daily W_{irr} and the total dynamic head of the pumping system (TDH) expressed as follows:

$$E_{\mathrm{irr}}\,(\mathrm{kWh}) = \frac{0.00272\ \left(\mathrm{kWh\,m^{-3}.m}\right) \times W_{\mathrm{irr}}\ \left(\mathrm{m^3}\right) \times TDH\ (\mathrm{m})}{\eta_{ps}}, \tag{1}$$

where $0.00\,272(\mathrm{kWh\,m^{-3}.m})$ is the pumping energy intensity of water and η_{ps} is the efficiency of the pumping system. TDH is the algebraic sum of the elevation head (H_{evel}), operating pressure head of the pump (H_{pres}) and frictional head loss (H_{floss}) expressed as follows:

$$TDH = H_{\mathrm{elev}}\,(\mathrm{m}) + H_{\mathrm{pres}}\,(\mathrm{m}) + H_{\mathrm{floss}}\,(\mathrm{m})\,. \tag{2}$$

The H_{elev} is composed of the depth-to-groundwater table (DTW) at rest and the drawdown (H_s) induced by pumping. In this paper, we estimate drawdown using the Theis analytical solution for a single-well model, as adopted by Xie *et al* [36], a detailed account is given by equation (9) in the supplement.

2.4. Groundwater recharge model

To assess the environmental sustainability of solar irrigation, we have developed a simplified groundwater availability assessment model. This model aims to mitigate environmental fallout dye to over-pumping in agro-ecological zones with insufficient groundwater recharge. We utilize long-term average annual groundwater recharge data from the British Geological Survey (BGS) [60] to calculate the net renewable water availability after irrigation withdrawals for each of the seven crops considered, across all 10 km gridded pixels. A cropland cell is deemed unfeasible for solar irrigation development if the net renewable water recharge after irrigation withdrawals is negative. In this simplified model, we assume that each gridded cropland cell is homogeneous and independent of adjacent cells, implying no lateral groundwater or irrigation water flows among gridded cropland cells. This assumption allows for the independent estimation of net groundwater recharge for each cell as follows:

$$W_{\text{avail},t} = \begin{cases} (R_t - W_{C,t}); & \text{if } R_t \geqslant W_{C,t} \\ 0; & \text{otherwise} \end{cases} \tag{3}$$

where $W_{\text{avail},t}$ represents the annual renewable water availability, R_t denotes the long-term groundwater recharge estimated by BGS [60], and $W_{C,t}$ is the annual crop water requirement unmet by natural precipitation and available soil water content. In this study, the 10 km gridded cropland pixel is treated as a recharge surface, and $W_{C,t}$ is confined to the cropland cover within each pixel. Thus, the annual groundwater recharge (in m^3) is calculated across the entire 10 km gridded pixel, while the evapotranspirative demand of the crop met by irrigation ($W_{C,t}$) is computed over the cropland cover within the pixel.

It is important to note that while the recharge amount R_t from GBS is an initial determinant of the feasibility for sustainable irrigation, it does not incorporate the additional water requirements ($W_{C,t}$) of potentially irrigated crops not currently grown. Therefore, a comprehensive assessment of sustainability must take into consideration $W_{C,t}$ for crops that might be introduced through irrigation.

2.5. Economic feasibility of irrigation

In this study, we employ a benefit-cost analysis to determine the economic feasibility of irrigation. That is, besides environmental sustainability, a cropland pixel is deemed economically feasible to irrigate if its NPV of cashflows associated with irrigation is positive. That is, the net present revenue (NPR) from irrigation yield gain of a given crop is greater than the net present cost (NPC) of the irrigation system. In general, we express the irrigation NPV as follows:

$$NPV = \sum_{t=1}^{n} \left(\frac{C_{p,t} \times \Delta Y_t}{(1+r)^t} \right) - \left(C_0 + \sum_{t=1}^{n} \frac{C_{\text{trans},t} + C_{\text{om},t}}{(1+r)^t} \right), \tag{4}$$

where ΔY_t, $C_{p,t}$, $C_{\text{trans},t}$, and C_0 are, respectively, the irrigation yield gain in year t, the annual crop price in \$/ton, transport cost of delivering crops to markets (see section 4.3 in the supplement for a detailed account), and the initial capital cost comprising of the investment costs for the pressurized irrigation system, well drilling and development costs, water conveyance system, irrigation pump, water storage, and the associated installation and commissioning costs estimated from prior studies [61, 62]. $C_{\text{om},t}$ is the annual operating and maintenance costs of the irrigation system and the borehole, including replacement costs. In computing irrigation profitability (\$/ha), we assume that labor, agro-chemicals, seeds, and farm preparation costs for rainfed and irrigated production are comparable and as a result, they can be ignored in the model for estimating the NPV due to extra yield from irrigation as in [27]. The key cost data and their related assumptions used in the economic module to estimate irrigation NPV are given in table SI 5 in the supplement.

3. Sensitivity analysis

To account for the inherent uncertainties in our model, which stem from factors such as system costs (shown in table SI 5 in the supplement), uncertainties in groundwater depth as reported by Bonsor and MacDonald [63], uncertainties in applicable discount rates (shown in table SI 6 in the supplement), and the uncertainties in fertilizer application rates due to farmers' difficulties in obtaining agricultural inputs, we have integrated a cost-based sensitivity analysis into our research study. We delineate two cost scenarios: 'low-cost' and 'high-cost' based on the technology costs distributions (shown in table SI 5 in the supplement), national variations in the WACC, and discrepancies in groundwater levels [52]. The 'low-cost' scenario combines the lower bounds of irrigation infrastructure costs and the lower bounds of the national-level WACC values (given in table SI 6 in the Supplement). In contrast, the 'high-cost' scenario combines the upper bounds of system cost estimates and WACC value ranges. In the general sense, the 'low-cost' scenario represents an optimistic case, with cost variables set at their lowest, whereas the 'high-cost' scenario represents a cost-intensive situation, with all cost variables at their maximum. It is important to highlight the uncertainty of groundwater depth in SSA and its implications for solar irrigation development. According to Bonsor and MacDonald [63], groundwater depth in SSA, at 2.5 arc-min (about 5 km at the equator) resolution, is categorized into various depths as follows: 'very shallow' (0–7 m), 'shallow' (7–25 m), 'shallow to medium' (25–50 m), 'medium' (50–100 m),'deep' (100–250 m) and 'very deep' (> 250 m).

Another major source of uncertainties in our model is fertilizer application rates. 10% of the farmers in SSA region grow crops without any artificial fertilizer application while 50% of those who use fertilizers rely on low-value organic fertilizers with significant impacts on crop yields [44]. This is largely due to the high cost of inorganic fertilizers beyond the SSA's smallholder farmers' affordability. We integrate these uncertainties in fertilizer usage on irrigation feasibility by considering four fertilizer application levels: optimal (100f), near-optimal (85f), moderate (50f), and low (25f), as in [27, 47]. While higher fertilizer application rates naturally lead to increased production costs, our paper does not incorporate the incremental cost of fertilizer inputs into the analysis. This exclusion is due to the difficulties in obtaining accurate, localized fertilizer pricing, particularly within the SSA context. Consequently, while this assumption may compromise the precision of our irrigation profitability estimates-especially at the reduced fertility levels which imply reduced production costs-the overall trends are expected to remain valid. Declining soil fertility correlates with a reduction in yield, which, in turn, reduces the irrigation profit margins, in line with findings from [47, 64].

4. Results and discussion

4.1. Preliminary geospatial analysis

Figure 2 shows spatial mapping of the current rainfed cropland, solar insolation, average annual rainfall, and groundwater attributes (productivity, depth, and recharge), all delimited to the cropland, at 10 km resolution. In generating the maps shown in the figure, we have excluded the cropland pixels that are not feasible for solar irrigation based on the study inclusion/exclusion constraints listed in table 1.

The groundwater recharge map for the SSA sub-continent is derived from the long-term average annual recharge data from the BGS [60]. As illustrated in the figure, all mapped features and attributes demonstrate significant spatial variability. Notably, the density of rainfed cropland is highest in Central Ethiopia and West Africa, particularly in Nigeria, Ghana, and Ivory Coast. Meanwhile, Central and West African regions experience the highest rainfall and groundwater recharge. These spatial variations in groundwater attributes (depth, yield, and recharge) and climate attributes (rainfall and solar insolation) have significant implications for solar irrigation feasibility, which is further explored in the subsequent sub-sections of this paper.

4.2. Irrigation requirement, system capacity, and costs

Irrigation requirements (W_{irr} and E_{irr}) as well as the associated system capacity and capital costs, depend on several factors such as crop type and location-specific soil and climate attributes, primarily temperature and precipitation. In figure 3, we spatially map out the average annual (20-year average) E_{irr}, per-hectare solar PV system size, and the associated capital costs for solar irrigation system based on tomato crop; most irrigation-intensive crop among the seven crops considered in our study. The sub-regional average W_{irr} and E_{irr} for each of the seven crops are presented in figure 4. The 10km gridded simulations results, including irrigation requirements and increase in yield due to irrigation are available in a Zenodo repository (Wamalwa *et al* 2024). The results highlight regional disparities in irrigation requirements, with some agro-ecological zones requiring significantly high E_{irr}, irrigation system sizes and the associated capital costs than others. For instance, the Central and West African regions require lower E_{irr} and lower capital costs compared to the Sahel region and Southwest Africa. These differences are explained by the spatial disparities in SSA's climatic conditions and groundwater attributes (mainly depth), as illustrated in figure 2. The solar pump capacities correlate with E_{irr}, indicating that regions with higher E_{irr} necessitate larger solar pumps.

In general, the interaction among these three variables, as depicted in figure 3, influences the solar irrigation feasibility within a given agro-ecological zone. Regions with high irrigation requirements-such as the Sahel, Somalia, and Southwest Africa-have steep initial capital costs, which can impact the long-term

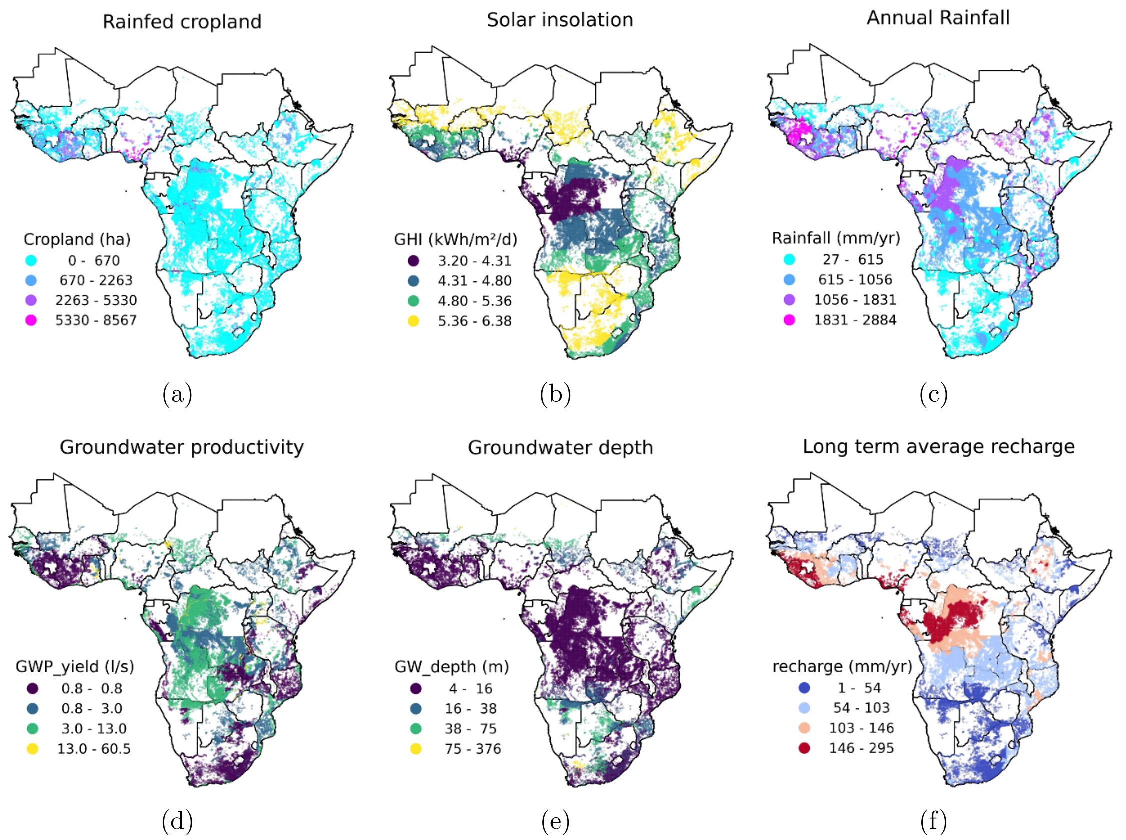


Figure 2. Rainfed cropland (a); long term average solar insolation (b); average annual rainfall (c); average groundwater aquifer productivity (d); average groundwater aquifer depth (e); and long term average annual groundwater recharge (f).

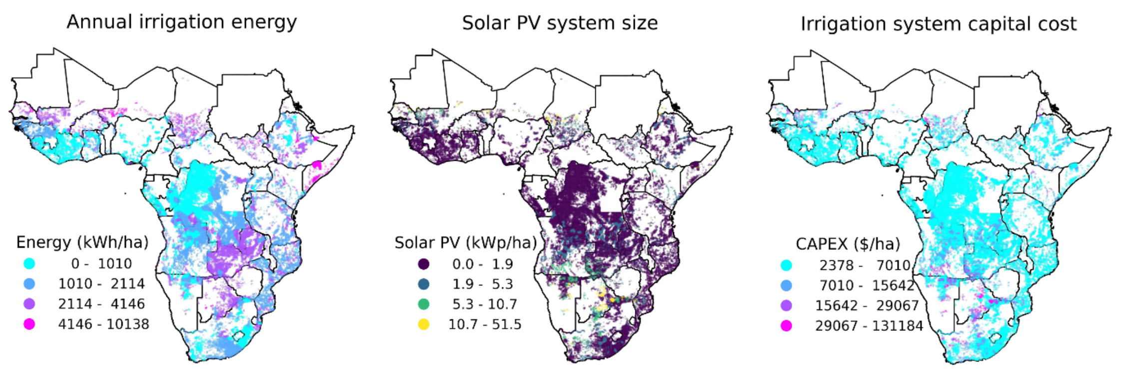
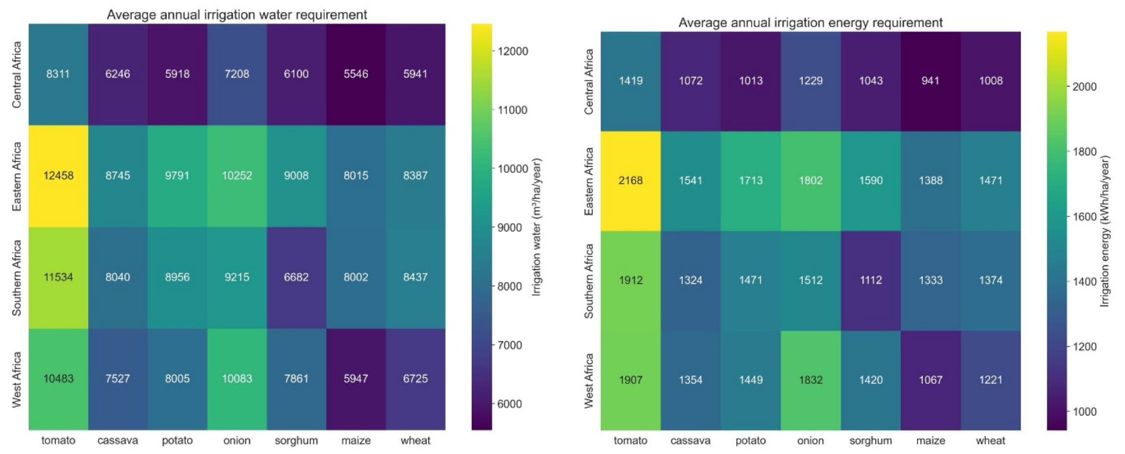


Figure 3. Average annual per hectare irrigation water requirement (a); solar pump per hectare system capacity (b); per hectare solar irrigation system's capital cost (CAPEX) (c).

economic viability of solar irrigation. Conversely, regions characterized by low irrigation requirements may find solar irrigation development unviable due to insufficient agronomic returns.

Figure 4 illustrates how irrigation requirements vary with crop types and regional agro-climatic conditions. Notably, tomato and maize crops have the highest and lowest irrigation requirement, respectively, across the four SSA sub-regions. Central Africa's lower irrigation requirements can be attributed to its higher rainfall intensity and lower solar radiation (see figure 2(b)). Besides solar irrigation system sizing, the results shown in figure 4 can be used by policy-makers and energy infrastructure planners as a high-level decision-making reference on local to country-level energy infrastructure planning for irrigation uptake, when the cropland area earmarked for irrigation is known.



(a) (b)

Figure 4. 20-year average annual irrigation water (a) and energy (b) requirement for the seven crops grouped by SSA sub-region. Refer to figure SI 7 in the supplement for geographical delineation of the four SSA sub-regions and the countries comprising them.

4.3. Economic benefits of irrigation

In figure 5, we spatially map the annual per-hectare irrigation profitability for a select range of crops–including two horticultural (onion and tomato), two tuber (potato and cassava), and two cereal crops (wheat and sorghum)–assuming optimal soil fertility conditions (100f) and median cost and discount rates. An exhaustive evaluation of all seven crops considered in our study at varying soil fertility levels is presented in section SI 5.5 of the supplement, including regional and crop-specific annual irrigation yield gains. In our irrigation feasibility analysis, we exclude cropland cells deemed unfeasible for solar irrigation, according to the constraints described in table 1, and those resulting in a negative NPV for irrigation. Our findings, as shown in figure 5, underscore that irrigation profitability varies by crop type and geographic location. Horticultural crops (onion and tomato in this case), and cereal crops (particularly maize and wheat) typically represent the most and least profitable categories, respectively.

We further show the aggregated results of the effects of fertilizer application rates on irrigation feasibility in figure 6. The first row is crop-specific irrigation profitability while the second row shows the corresponding crop-specific viable cropland area under different soil fertility conditions. As shown in the figure, irrigation feasibility decrease with a decrease in fertilizer application rates, underscoring the importance of optimal fertilizer application rates in maximizing irrigation benefits. A notable observation is the varying sensitivity of irrigation profitability to changes in soil fertility among the seven crops. The cassava crop exhibits less sensitivity to changes in soil fertility in comparison to cereal crops, particularly maize and wheat. Even at a lower soil fertility level of 25f, irrigating cassava remains profitable, whereas irrigating maize under the same condition is not economically feasible.

Variability in irrigation feasibility across the four SSA sub-regions for optimal soil fertility (100f) for the seven crops is further explored in figure 7, with a detailed country-level breakdown presented in tables SI 8 and SI 9 in the supplement. The results show that an estimated 9.34 million ha–averaged across the seven crops–of SSA's current rainfed cropland is feasible for solar irrigation. Among these, maize and onion crops exhibit the lowest and highest irrigation feasibility, with 1–4 million ha and 29–33 million ha, respectively, based on cost scenarios. The obtained results are consistent with the findings in other studies in the current literature. According to Xie *et al* [65], an estimated 6–14 million ha of SSA's arid/semi-arid land (comprising mainly of the current rainfed cropland) are feasible for irrigation, with small-scale irrigation (consistent with hectare scale solar irrigation considered in this study) accounting for 9.1 million ha. The results from figure 7 further reaffirm the dependency of irrigation feasibility on geographical location and crop type.

Among the cereal crops, maize and sorghum show the lowest and highest annual irrigation-induced profitability over a 20-year period (2001–2020), averaging $50-125/ha and $240-410/ha, respectively, across 1–4 million ha and 3–5 million ha of cropland. The lower and upper bounds of these feasibility figures correspond to high-cost and low-cost scenarios, respectively. The two tuber crops studied in this paper-that is, cassava and potato-yield comparable levels of irrigation feasibility, with cassava generating annual profitability of $510–750/ha over 6–10 million ha and potato achieving $510–790/ha across 6–8 million ha.

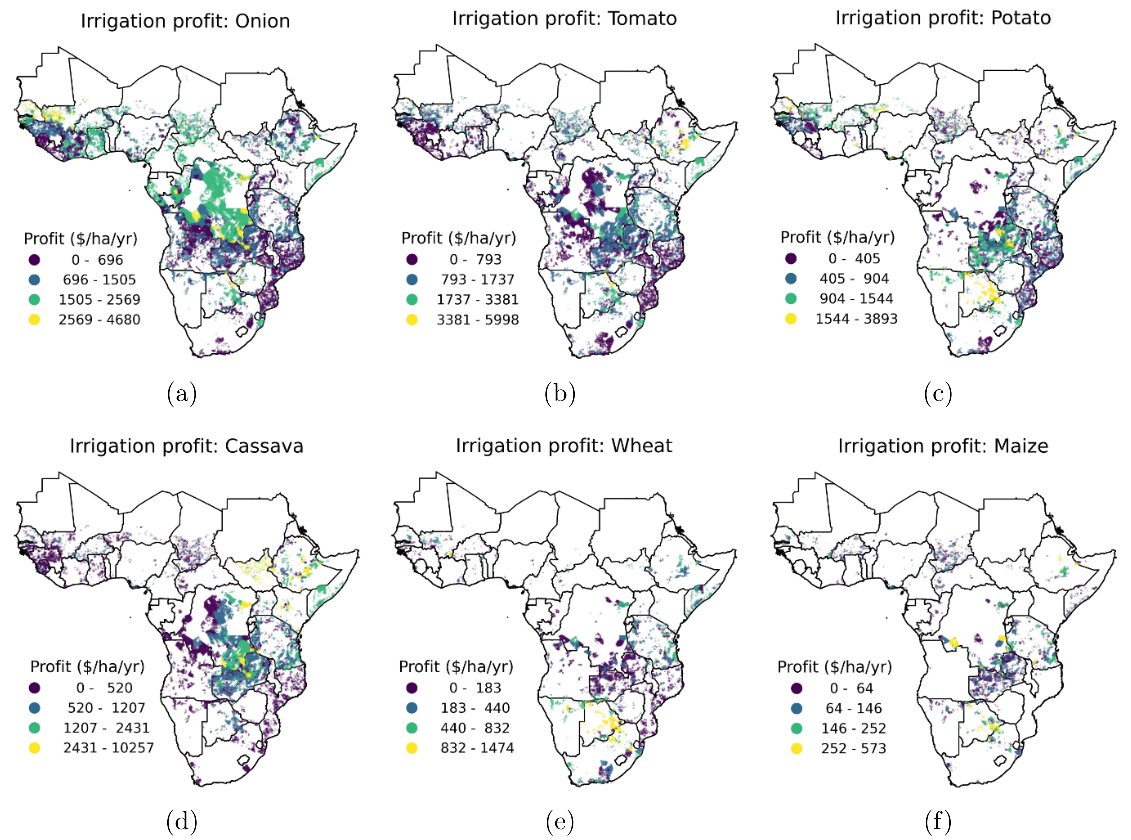


Figure 5. Annualized per-hectare irrigation profitability for select horticultural (onion and tomato), tuber (potato and cassava), and cereal (wheat and maize) crops, assuming median system cost estimates and optimal soil fertility.

For the horticultural crops—onion and tomato in this paper–the onion crop emerges as more profitable, generating an average annual profit of $930–1450/ha over a feasible cropland area of 29–33 million ha, depending on cost scenarios, under optimal soil fertility conditions. In comparison, the tomato crop yields an average annual return of $790–1240/ha over 8–11 million ha under the same optimal soil fertility conditions. Furthermore, our findings indicate that the feasibility of solar irrigation for these crops is region-specific: West Africa provides high economic returns for potatoes, while Eastern Africa is more profitable for maize, sorghum, tomato, and cassava. Central Africa and Southern Africa are most profitable for onion and wheat, respectively.

In general, the SSA region presents significant potential for solar irrigation, as discussed in section 4.4. The variability in irrigation feasibility across different crops aligns with findings from other studies; namely, the irrigation of staple crops commonly cultivated by smallholders on 1-2 ha-such as maize, beans, and wheat-is often the least profitable [27, 40] due to their lower market values [18]. Conversely, high-value horticultural crops like onions and tomatoes are more economically gainful to irrigate [27, 47].

4.4. On food security implications of irrigation

Table 2 shows a summary of imports, exports, and irrigation yield gain for the cereal crops considered in our study (maize, wheat, and sorghum) between 2010 and 2020, the years with available data for the three crops from FAOSTAT [66]. The irrigation yield gains in the table are the increase in yield due to irrigation farming of the three cereal crops in the cropland pixels that are hydrologically and economically feasible for solar irrigation, assuming optimal soil fertility conditions. The comparative results show that irrigation farming has potential to achieve food sufficiency for sorghum–irrigation yield gain is higher than the imports—and reduce maize and wheat imports by 15% and 3%, respectively. Detailed country-level results are presented in table SI 10 in the supplement. Although the regional aggregate results of maize and wheat are modest compared to sorghum, at the country level, up to 10 of the 39 countries in SSA (table SI 10) that were net importers of maize between 2010 and 2020 would fully satisfy their local demand and even generate a surplus for export through irrigation.

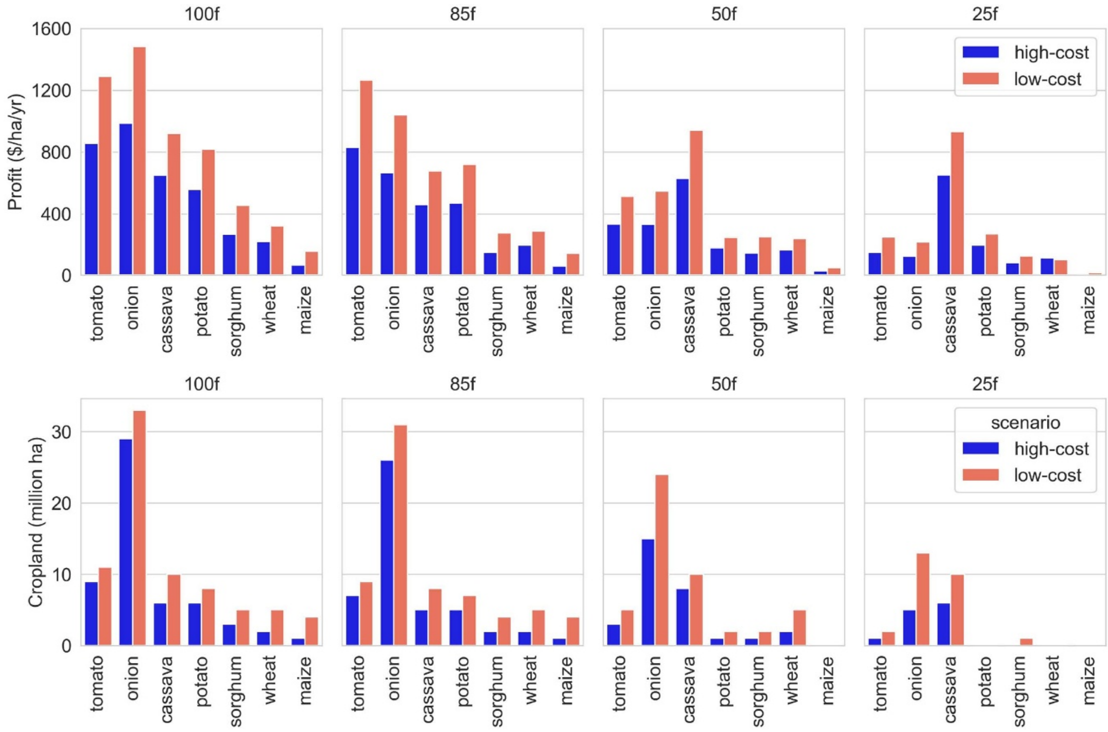


Figure 6. Solar irrigation viability by cropland area (in million ha) and the corresponding per-hectare annual profitability at different soil fertility conditions. 100f, 85f, 50f, and 25f are respectively, optimal, near-optimal, medium, and low fertilizer application rate.

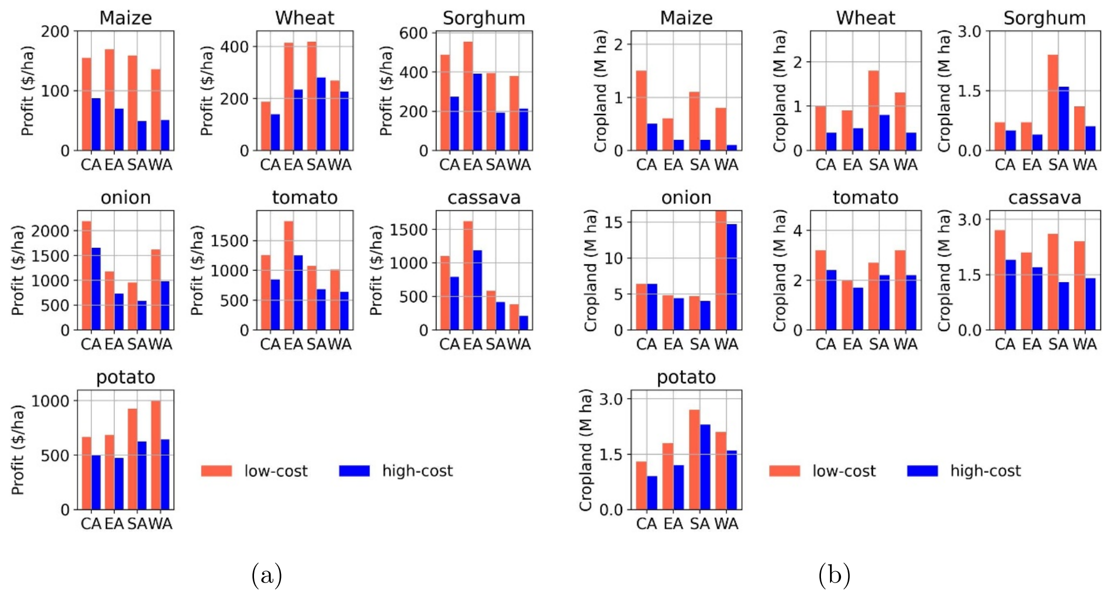


Figure 7. Annualized per-hectare irrigation profitability (a) and the corresponding viable cropland in million ha (b) for the seven crops considered in our study, assuming optimal soil fertility conditions.
Note: The 'low-cost' and 'high-cost' refers to low and high cost irrigation system cost scenarios described in sub-section 3. In the figure, CA, EA, SA, and WA are respectively, Central Africa, Eastern Africa, Southern Africa, and West Africa. Refer to SI 7 in the supplement for geographical delineation of these regions in SSA.

Although food self-sufficiency is not an essential precondition for food security, as noted by van Ittersum *et al* [67], it plays a pivotal role in low-income countries, particularly those in SSA, where economic development is heavily reliant on agriculture productivity [68]. It is also crucial to recognize that many developing nations in SSA do not have sufficient foreign exchange reserves to pay for food imports [67], making self-sufficiency in food production fundamental to achieving food security. From a different perspective, reducing reliance on food imports can also enhance food security by lowering food prices, which

Table 2. A comparison of import, export, and yield gain due to irrigation of a maize, wheat and sorghum crops in SSA [66].

Item	Maize	Wheat	Sorghum
Import (million tons)	63.9	252.2	6.8
Export (million tons)	35.5	12.1	2.2
Yield gain (million tons)	9.3	7.99	34.9

Import is the net food import as a share of total food supply. Yield gain is the aggregated increase in yield due to irrigation of the feasible (both economically and hydrogically) cropland over the 10-year period (2010–2020), assuming optimal soil fertility conditions

are significantly influenced by global market trends [42]. High global food prices typically result in higher local prices for heavily imported food crops, such as wheat, as illustrated in table 2. Conversely, increasing local production of staple food crops can lead to lower local food prices by decreasing dependence on imports [42].

5. Discussion and recommendations

In this study, we integrated a hydrological model, a biophysical crop model, and a techno-economic model to evaluate the sustainability of irrigation water withdrawals, estimate crop yields and irrigation requirements, and assess the technical and economic feasibility of solar irrigation in SSA's rainfed cropland. The irrigation feasibility results presented in this paper are consistent with findings in previous studies, such as those by Falchetta *et al* [41] and Xie *et al* [39], reinforcing the robustness of our modeling process and outcomes. On average, across the seven crops analyzed, an estimated 9.34 million ha of SSA's current rainfed cropland are hydrologically and economically feasible for solar irrigation, assuming median cost estimates and optimal soil fertility conditions. This finding corroborates the findings by Xie *et al* [39], who estimated a small-scale irrigation potential of 9.1 million ha in SSA's arid and semi-arid lands. Our profitability range is consistent with that reported by Falchetta *et al* [41]. However, it is important to note that merely quantifying irrigation potential does not guarantee widespread adoption of solar irrigation, due to significant barriers such as the high costs of irrigation infrastructure [22, 23] and inadequate market linkages [24].

Our results indicate that annual irrigation profitability for low-value crops like maize, wheat, and sorghum ranges from $50–410/ha, covering an area of 1–5 million ha, depending on the specific crop and cost scenarios. The modest economic returns from irrigating these crops at the technology costs used in our model underscore the need for cost reduction strategies to enhance both spatial and economic feasibility. The current high costs of solar pumps and irrigation infrastructure development, are prohibitive for smallholder farmers, underscoring the need for financial instruments to facilitate solar irrigation adoption. The recent increase in solar irrigation adoption in SSA is largely attributed to the decline in solar PV technology costs [69], efforts by development partners and donors [17], and, to some extent, governments' economic incentives. Import tax relief for solar pumps has demonstrated potential to boost the affordability and uptake of solar irrigation in developing regions and countries such as Ethiopia [70]. Similarly, the success of solar irrigation in the Middle East and North Africa (MENA) region, particularly Egypt and Morocco, and in South Asia, particularly in India, has been partly driven by reductions in capital costs and the elimination of trade tariffs [21]. This evidence suggests that cost reduction incentives have a significant role in expanding the adoption of solar irrigation in SSA.

Besides access to irrigation technology, the availability and access to markets (both for farm inputs and the sale of crop produce) is crucial for the accelerated and sustained adoption of solar irrigation technology in SSA. Our analysis has demonstrated that the economic benefits of solar irrigation are significantly influenced by transport costs, which are a critical aspect of market access. This is especially true in sparsely populated agro-ecological zones such as Somalia, Botswana and South West Africa. The cost of transporting agricultural proceeds to potential market locations (urban centers with a minimum population of 20 000 people in this case) derail profit margins in these locations. Furthermore, it is important to note that despite the substantial yield gaps, up to 15% of the food crops produce in SSA are lost in post-harvest handling, largely due to poor market access [57, 58] and lack of storage capacity [57]. The informal nature of food markets makes it difficult to predict food demand, and as a result many smallholder farmers produce for speculative markets infested with middlemen who manipulate market information to financial detriment of farmers [22, 71]. This, coupled with smallholder farmers' limited knowledge of crop markets, results in losses, especially in seasons with yield gluts. Efforts are required to formalize food markets and distribution channels if the projected irrigation benefits are to benefit the farmer and sustain irrigation adoption, noting that the farmers' ability to pay for irrigation technology costs (where credit is advanced) is tied to the profitable sale of the extra yield.

Lastly, our analysis highlights the critical importance of using the appropriate amount of fertilizers to realize the optimal benefits of irrigation. According to Vanlauwe *et al* [44], 10% of farmers in the SSA region do not use any fertilizers and 50% of those who use fertilizers rely on low-value organic options, resulting in sub-optimal yields. Our results show that it is least viable to irrigate in most of the current rainfed croplands at very low fertilizer application rates (25f in this case), consistent with the findings in [27]. Therefore, we argue that access to and use of the right quantity of fertilizers are critical for achieving optimal agronomic and economic benefits of solar irrigation [72].

6. Conclusion

In this study, we have used seven representative food crops commonly grown in SSA (viz: namely maize, wheat, sorghum, potato, cassava, tomato, and onion) to assess both the cropland area and the economic feasibility of solar irrigation in the region's current rainfed croplands. We carry out the analysis at a 10 km spatial resolution over a 20-year period (2001–2020). For irrigation yield gain, we rely on simulated yields from the FAO's AquaCrop model due to data scarcity. We deem a cropland pixel (10 km gridded cropland cell) as economically feasible for solar irrigation if the NPV of cash flows from increased yields due to irrigation of it exceed the 20-year life cycle costs (LCC) of the irrigation system.

Our study incorporates a sensitivity analysis to assess the impact of uncertainties in system cost parameters such as discount rates and technology costs, as well as soil fertility, on the feasibility of solar irrigation. Our study findings reveal that solar irrigation feasibility is highly dependent on the type of crop grown, irrigation system cost scenarios, agro-climatic zones, and soil fertility levels. This aligns with observations by Sheahan and Barrett [73] and Izar-Tenorio *et al* [47], who noted the economic benefits of combining irrigation with optimal fertilizer application.

From the seven crops considered in out study, we find that horticultural crops–tomato and onion in this case–are the most feasible crops to irrigate. Over the 20-year period, tomato and onion crops yield annual profits of \$790–1240/ha and \$930–1450/ha, respectively, under optimal soil fertility conditions, depending on the cost scenarios (low vs. high). In contrast, maize is the least profitable crop, with annual profitability of \$100–170/ha, depending on cost scenarios. The economically viable cropland area also varies, with onions having the highest potential area (29–33 million ha) and maize the least (1–4 million ha), depending on the cost scenarios. Further exploration of the effects of fertilizer application rates on irrigation feasibility was conducted through a scenario-based sensitivity analysis covering four soil fertility conditions: optimal (100f), near-optimal (85f), moderate (50f), and very low (25f). This analysis suggests that irrigation is most viable at near-optimal to optimal fertilizer application rates, and least viable under the 25f fertility condition, corroborating findings by Sheahan and Barrett [73].

At a sub-regional level, Eastern Africa is the most profitable sub-region for solar irrigation of maize, sorghum, tomato, and cassava crops, while Central Africa is most profitable for onions. Meanwhile, West and Southern Africa are more economically attractive for potato and wheat crops, respectively. To realize the solar irrigation benefits presented in this study, an estimated annual irrigation energy of 941 to 2168 kWh/ha/year is necessary over the analyzed period, with specific requirements varying by crop and geographic location.

Our model and the results thereof can be used as a high-level decision-making reference for solar irrigation planning in SSA, specifically in understanding where it is feasible to irrigate and the required capital investment as well as expected return on investment based on the seven crops we have considered. Practical implementation of solar irrigation projects require a more detailed analysis, including inputs from agricultural engineers, irrigation developers/planners, agricultural extension, detailed environmental analysis, food markets assessment, and consideration of surface water potential, which is not considered in our work. While our study utilizes historical records, particularly climate data, future research advancement will focus on forecasting the impacts of climate change on irrigation requirements in SSA. Importantly, we contemplate exploring the potential for nexus projects, such as integrating irrigation energy requirement in spatial electrification planning of the SSA region. Currently, electrification in SSA is advancing at a slow pace, largely due to the limited viable electricity demand from the rural demographic. By integrating the productive use of electricity into electrification planning, there is significant potential to overcome the low demand barrier and accelerate electrification. Such integration not only addresses immediate energy needs but also supports sustainable agricultural practices, thereby enhancing the overall development trajectory of the SSA region.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.11 080 370 [74].

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