LETTER

Techno-economic feasibility of small-scale pressurized irrigation in Ethiopia, Rwanda, and Uganda through an integrated modeling approach

Jorge I Izar-Tenorio 1, 2, Paulina Jaramillo 1, 3 and Nathan Williams 1, 2, 3

1 Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213, United States of America
2 Golisano Institute for Sustainability, Rochester Institute of Technology, Rochester, NY 14623, United States of America
3 Kigali Collaborative Research Center, Kigali, Rwanda

* Author to whom any correspondence should be addressed.
E-mail: jizarten@andrew.cmu.edu

Keywords: small-scale irrigation, techno-economic analysis, electricity use, East Africa

Abstract

Agriculture contributes up to 50% of the gross domestic product in some East African countries and is the backbone of the region’s economy. Most farmers rely on traditional, small-scale subsistence farming with low fertilizer use and low-yield seeds. Similarly, less than 3% of the total cultivated area employs any form of irrigation, mostly non-pressurized. Meanwhile, electricity providers frequently struggle with low and unpredictable demand, challenging their ability to recover rural infrastructure investments. Using electricity to pump irrigation water can increase agricultural productivity and improve the financial sustainability of rural electricity supply. This study evaluates the productive and economic feasibility of pressurized small-scale irrigation systems in Ethiopia, Rwanda, and Uganda for three staple crops and two horticulture crops. To study these effects, we develop simplified engineering-based irrigation and hydrology models and combine them with an existing biophysical crop growth model using district-level agrometeorological, soil, and crop physiology data as inputs. Our results indicate that small-scale pressurized irrigation can significantly increase yields for horticulture crops and staples such as maize or potato grown with improved seeds and moderate or greater fertility levels. The sensitivity analysis shows that irrigation may be techno-economically viable in up to 36% of Ethiopian woredas, 67% of Rwandan districts, and 45% of Ugandan districts provided the use of improved cultivars and non-limiting fertility conditions. These results highlight the value of complementing irrigation investments with electricity infrastructure in East Africa.

1. Introduction

Agriculture is the backbone of East Africa’s economy, contributing up to 50% of gross domestic product (GDP) and employing more than 80% of the workforce in some countries (Schaffnit-Chatterjee 2014). More than 95% of the agricultural holdings in East Africa are smaller than 10 hectares (ha) (i.e. small-scale) and rely on traditional agricultural practices. Less than 4% of the total cultivated area in East Africa employs some form of irrigation (Svendsen 2009), while fertilizer use (2–14 kg ha$^{-1}$) is among the lowest in sub-Saharan Africa (SSA), where average fertilizer use is 16 kg ha$^{-1}$ (the lowest in the world) (World Bank 2017). At the same time, electricity providers in the region struggle with low and unpredictable demand, which challenges their ability to recover infrastructure investments in rural areas. The informal nature of markets along corresponding value chains poses an additional challenge for further economic development and food security (Mwamakamba et al 2017).

Numerous studies reveal the potential benefits of strengthening agricultural value chains through electricity consumption in Africa. Schaffnit-Chatterjee (2014) suggests that investing in agricultural value chains is key to sustained economic growth, poverty reduction, and food security in SSA. Banerjee et al...
identify irrigation and post-harvest processing as the most promising agricultural activities to boost SSA's productivity and economic growth through improved access to modern electricity services. Nordhaus et al. (2019) note that economic development occurs as part of a virtuous cycle of agricultural modernization, energy consumption, and universal electrification. These observations support the idea that the development of electricity and agricultural systems should go hand in hand in the pursuit of rural development.

Despite its vast water resources, SSA's farmers withdraw only 3% of its renewable water resources for irrigation (Swensden et al. 2009, Schaffnit-Chatterjee 2014). This limited irrigation use is due to high capital costs, poorly developed supply chains, and a lack of knowledge about irrigation schemes' benefits and technologies (Cornish 1998, Kay 2001, Giordano et al. 2012). Along with irrigation and post-harvest processing, the use of fertilizers and improved seed varieties could further enhance agricultural productivity (Sheahan and Barrett 2017).

Only a handful of studies evaluated the financial benefits and costs of pressurized irrigation systems combined with other resources that support the activity, such as nutrient inputs and water resources availability. Schlenker and Lobell (2010) used a statistical model to show that higher yields correlate positively with precipitation for most SSA countries' crops. Waldhoff et al. (2020) found country-level yield reductions under projected future climate scenarios using an empirical model. Calvin and Fisher-Vanden (2017) found that integrated assessment models generate higher yield increases under future climate change than process-based or statistical models in the US. Rosegrant et al. (2009) and You et al. (2011) found that irrigation systems' profitability in Africa is not homogeneous. None of these prior studies assessed irrigation's electricity requirements, which is a critical input often lacking in agricultural areas in the least developed countries. Similarly, these studies focused mainly on national scales and neglected to include agricultural inputs such as fertilizer or soil characteristics.

Our study contributes to the literature by assessing the interaction of several critical inputs on crop yields, including electricity demand for irrigation, soil texture, fertility levels, cultivar type, and water availability for irrigation. We use an integrated approach that combines irrigation and hydrological models (that we developed based on engineering relations) with an existing biophysical crop growth model to evaluate the techno-economic viability of small-scale pressurized irrigation systems.

We selected Ethiopia, Rwanda, and Uganda as case studies for multiple reasons. First, they are among the fastest-growing economies in SSA by GDP per capita growth in the last 20 years (World Bank 2021a). These countries also have a history of chronic hunger and famine (Hasell and Roser 2013, Reid 2021), and some projects to experience severe food insecurity in the next year (FEWS NET 2021). Moreover, according to the Food and Agriculture Organization (FAO), their share of food imports over the last few years is considerable (FAO 2021), especially for staples. Additionally, their high population density (World Bank 2021b) can challenge the availability of land for agriculture, making them ideal case studies for studying the impacts of agricultural intensification through irrigation.

2. Materials and methods

Our modeling framework combines a biophysical crop growth model, AquaCrop, with a simplified engineering-based irrigation model to estimate yields, electricity demand for pumped irrigation, and water use for irrigation. We use AquaCrop to simulate crop yields and net irrigation requirements using climatological, soil, and crop physiology data as inputs. We then use AquaCrop's simulated irrigation requirements to estimate the electricity consumption for irrigation, assuming groundwater as the water source and a pressurized irrigation system design.

A pressurized irrigation system enables the distribution of water under pressure through pipes as opposed to gravity systems that use height differences for water to flow. It also allows irrigators to apply more precise water quantities and avoid water losses due to percolation, soil surface absorption, and evaporation, thus improving irrigation performance efficiency (Cornish 1998, Chauhdary et al. 2017). The most common types of pressurized irrigation are drip and sprinkler systems (Swensden et al. 2009, Chauhdary et al. 2017).

Finally, we estimate water availability based on a groundwater recharge method. Figure 1 briefly describes the integrated modeling approach, while Table 1 summarizes the definitions, data inputs, and parameter values used to run the three models. More information about the data and parameter inputs is available in the supporting information (SI), sections S2.2–S2.4 (available online at stacks.iop.org/ERL/16/104048/mmedia).

AquaCrop is a water-driven biophysical crop growth model developed by the FAO of the United Nations. The model requires climate, crop, soil, and field management inputs from the user and relies on fundamental and often complex biophysical processes (Steduto et al. 2009, Raes et al. 2017). The model includes several pre-calibrated and validated crop files (Steduto et al. 2012, Raes et al. 2018a) ready for use in simulations. Numerous scholars validated AquaCrop and found robust yield estimates for various irrigated crops, including beans (Magalhães et al. 2019), maize (Akumaga et al. 2017), potato (Montoya et al. 2016), wheat...
Figure 1. Description of input data, modeling elements, and outputs of the integrated modeling approach.

(Andarzian et al. 2011), teff (Araya et al. 2010), onion (Pérez–Ortolá et al. 2015), and tomato (Darko et al. 2016). These and other scholars (Katerji et al. 2013, Yuan et al. 2013) showed that AquaCrop could provide accurate estimates over various climates from arid to semi-arid, Mediterranean, and humid climates. The resulting variables of interest from AquaCrop's simulations are yield (metric tons per hectare or t ha⁻¹) and irrigation water demand (mm).

We estimate the electricity demand for irrigation through a model based on Bernoulli's principle (Geankoplis 1998) and the methods described by Duke (2007) and Fipps (2017). This model assumes that the electricity demand for irrigation is a function of AquaCrop’s simulated water volume for irrigation, the total dynamic head (including the depth to the groundwater table for extraction), and the irrigation pumping system characteristics. More information on the parameter values used is available in section S2.3 of the SI. We characterize available water resources assuming groundwater as the source. This assumption is appropriate because groundwater is available virtually anywhere, while surface water is more site-specific and dependent on topography. Moreover, surface water is more prone to pollution and has more competing end uses (e.g. domestic and commercial water supply) than groundwater (Siebert et al. 2010).

Finally, we develop a simplified hydrological model following the methods in Rushton and Ward (1979), Alley et al. (1984), and Rodríguez-Huerta et al. (2020). The model assumes that monthly groundwater recharge occurs when precipitation exceeds evapotranspiration and runoff losses, and the soil-moisture equals the soil-moisture storage capacity. The complete mathematical formulation and assumptions of the model are available in section S2.4 of the SI. We validated our results with the estimates reported by SHER Ingénieurs-Conseils s.a. for the Rwandan National Water Resources Master Plan (RNWRMP). We find that our calculated average annual recharge rate for Rwanda (5330 Mm³ yr⁻¹) is slightly higher than RNWRMP’s reported recharge rate (4555 Mm³ yr⁻¹).

2.1. Simulation assumptions and outputs

We run simulations at a district-level resolution in Ethiopia, Rwanda, and Uganda using the centroid coordinate point (latitude, longitude, and elevation) as representative of each district. Subnational scales are more appropriate than national levels because differences in the microenvironment are more evident at higher resolutions. Our study's administrative boundaries include 690 woredas in Ethiopia, 30 districts in Rwanda, and 80 districts in Uganda, with an average district size of 1600 km², 800 km², and 2500 km², respectively. Information about each district’s centroid coordinate points is available in section 2.2.5 of the SI.

We select three staples and two horticulture crops for simulation in each country based on their relative national importance and productivity levels (FAO 2021). The selected crops are beans, maize, potato, tomato, and onions in Rwanda and Uganda, and maize, wheat, teff, tomato, and onion in Ethiopia. For each crop, in each district, we simulate ten years of meteorological conditions (2010–2019) with two planting seasons per year (dry and rainy), under four soil fertility levels (low, moderate, near-optimal, non-limiting), two water management modes (rainfed and...
Table 1. Summary of data and parameter inputs used in the modeling framework.

| Data type            | Input data or parameter                                      | Used in                      | Resolution        | Source                                                                 |
|----------------------|-------------------------------------------------------------|------------------------------|--------------------|------------------------------------------------------------------------|
| Climate              | Minimum and maximum temperature, mean relative humidity or dew point temperature ($T_{dew}$), wind speed, solar irradiance, latitude, longitude, and elevation (above sea level) → used to calculate evapotranspiration (ETo) with Penman–Monteith's equation. | AquaCrop, Hydrology model    | Daily, 50 km × 50 km | NASA POWER (Stackhouse 2019)                                           |
| Soil                 | Depth, texture in % sand, % silt, % clay = used to calculate hydraulic soil water content at saturation (SAT) in %, volume of water at field capacity (FC) in %, volume of water at permanent wilting point (PWP) in %, saturated hydraulic conductivity ($k_{sat}$) in mm d$^{-1}$, available water capacity (AWC) in %, soil-moisture (S) in mm, soil-moisture storage ($\Delta S$) in mm, and soil-moisture storage capacity (STC) in mm. In conjunction with P and ETo, $\Delta S$ and STC are used to calculate groundwater recharge ($\Delta R$). | AquaCrop, Hydrology model    | Once, 1 km × 1 km          | Harmonized World Soil Database (HWSD) v1.2 (FAO/IIASA/ISRIC/ISSCAS/JRC 2012) |
| Crop physiology      | Conservative (e.g. canopy growth coefficient, maximum root water extraction in root zone, shape factor for water stress coefficient for canopy expansion) and non-conservative (e.g. length of flowering stage, time from sowing to start senescence, reference harvest index) parameters for the specific type of cultivar, including phenology and planting dates. | AquaCrop                      | N/A                | AquaCrop pre-calibrated files modified after 18 literature papers (see section S2.2.3 of the SI) |
| Field management     | Rainfed or irrigated mode; fertility levels: low, moderate, near-optimal, and non-limiting; no mulches and perfect weed management.                                                                 | AquaCrop                      | N/A                | AquaCrop                                                               |
| CO2                  | Atmospheric CO2, in ppm (default). Depth to groundwater table (DTW).                                                                 | AquaCrop, Irrigation model    | Yearly, global 5 km × 5 km | AquaCrop MacDonald et al (2012)                                        |
| Irrigation system parameters | AquaCrop's simulated net irrigation requirements (Irr), volumetric flow rate (Q), pipe's diameter (D), total dynamic head (TDH) including depth to groundwater (DTW), acceleration of gravity (g), pump's efficiency ($\eta$) = used to calculate electricity demand for irrigation ($E_{irr}$). | Irrigation model             | N/A                | AquaCrop's simulation, Geankoplis (1998), Fipps (2017)                  |

irrigated), and two cultivar variates per crop (low- and high-yield). Thus, for each district, we run 1600 simulations.

To perform the simulations described in figure 1, we made some general assumptions. We assume fixed planting dates for each country without changes over time. Second, water for irrigation comes from groundwater, with no cost for rights or licensing to extract water and without considering water quality or salinity. The irrigation system assumes constant values for model parameters (available in the SI), such as the pump's operating pressure or the pipe's physical characteristics, without considerations for topography or slopes.

The three main outputs of interest for this analysis are annual district-level yields, net irrigation requirements, and electricity demand for irrigation. Because AquaCrop simulates yields as dry matter, we convert dry into fresh weight yields by employing conversion factors indicating each crop's dry matter content. This calculation uses dry matter values of 90% for teff, 87.5% for beans, maize, wheat, 22.5% for...
potato, 6% for tomato (Raes et al 2018a), and 12.5% for onion (Hendriksen and Hansen 2001). The difference between rainfed and irrigated yields further serves to normalize the net irrigation requirements and the electricity demand for irrigation on a per ton basis. We use the simulations from the low fertility scenario as the reference case because the district-level MapSPAM yields (IFPRI 2020) for the three countries and the latest official yields in Rwanda (NISR 2020) and Uganda (UBOS 2010) are consistent with the simulated yields for a low fertility scenario.

2.2. Techno-economic analysis
The techno-economic analysis relies on a combination of methods from Zhai and Rubin (2013), Zou et al (2013), and Campana et al (2015). We derive a levelized cost of irrigation (LCOI) as the present value of the irrigation system's costs divided by the additional metric ton of yield due to irrigation for each crop. This normalized metric is analogous to standard metrics used in the literature, such as the levelized cost of energy, the cost-effectiveness ratio of additional grain yields (Zou et al 2013), or the levelized cost of drinking water supply (Cooley and Phurisamban 2016). The present value of the costs includes the costs of building and operating the irrigation system assuming country-specific discount rates: 11% for Ethiopia, 15% for Rwanda, and 17% for Uganda (Ondraczek et al 2015). Section S2.5 of the SI includes the complete formulation of the LCOI calculations and the description of the input parameters. We then compare the LCOI to market crop prices from FAO (2021) data to evaluate the financial viability of the irrigation system. Finally, we perform a sensitivity analysis to assess the effect of electricity prices on the LCOI.

3. Results and discussion
3.1. Yield increase and water and electricity demand for irrigation
This section highlights the yield and water demand results of a baseline scenario that assumes the use of improved cultivars and low soil fertility levels. While we have results for simulations over ten years, the figures in this section highlight average annual values. The SI includes the average yearly results for other cultivars and fertility levels. The results of the 1600 simulations for each district are available in a Zenodo repository (Izar-Tenorio et al 2021).

Figure 2 shows that the highest average annual yield increases due to irrigation in the baseline scenario occur in Ethiopia’s Central and Western woredas, Rwanda’s Central and Southern districts, and Uganda’s Northern and Northeastern districts. For instance, irrigation can increase average annual country-level yields for maize grown with low soil fertility in Ethiopia from 2.7 to 5.1 metric tons per hectare (t ha\(^{-1}\)) for improved cultivars and from 2.1 to 3.3 t ha\(^{-1}\) for traditional varieties. In Rwanda, irrigation increases maize yields from 5.2 to 5.8 t ha\(^{-1}\) for improved cultivars and 3.4 to 3.5 t ha\(^{-1}\) for traditional cultivars. In Uganda, maize yields rise from 4.3 to 5.2 t ha\(^{-1}\) for improved cultivars and 2.6 to 2.8 t ha\(^{-1}\) for traditional cultivars. We note that a hectare of cultivated land produces different yields for different crops, as shown by each crop panel’s different color scheme scale. Based on the percent median yield increase due to irrigation for the reference case, the more suitable crops for irrigation are (in decreasing order) tomato, onion, maize, teff, and wheat, in Ethiopia; and potato, tomato, onion, maize, and beans, in Rwanda and Uganda.

Figure 3 shows that irrigation requirements per ton for improved cultivars grown with low soil fertility are consistently high across crops in Southeastern Ethiopia, Northern Rwanda, and Southwestern Uganda. Perhaps more interesting is that districts in Central Ethiopia, Southwestern Rwanda, and Northeastern Uganda combine considerable yield increases and moderate irrigation requirements. This pattern suggests that those regions may be the most attractive for irrigation.

Figure 4 shows that the annual average electricity demand for irrigation per ton for improved cultivars with low soil fertility is highest for Eastern and Southeastern Ethiopia, Eastern and Northern Rwanda, and Southeastern Uganda. Of all crops, beans in Uganda and Rwanda have, by far, the highest average electricity demand per ton. Meanwhile, wheat in Ethiopia has the biggest range of electricity demand values, followed by beans in Uganda and teff in Ethiopia. In contrast, Rwanda has the lowest average electricity demand per ton for crops grown in the three countries. These differences are a direct consequence of the volume of water required for irrigation and the depth to the groundwater table.

The amount of water required to grow a plant can significantly vary depending upon agronomic, geological, and meteorological aspects such as climatic zone (e.g. rainfall and temperature variability), crop type, soil type and depth, and atmospheric carbon dioxide (Lambers and Oliveira 2019). Crops with deeper roots can hold and absorb more water if soil texture and depth are adequate for water drainage and transport purposes (Chavarria and dos Santos 2012). Because evapotranspiration depends on temperature, temperature variations can also influence crop-water relations (Lambers and Oliveira 2019). These factors can vary considerably depending on the district’s climate and agroecological zone. For instance, Ethiopia’s north-south alignment and spread across varied climate zones may lead to higher rainfall variability. Because crop-water relations are more or less constant for a specific crop (Steduto et al 2012), the irrigation water (to make up for insufficient rainfall) and electricity requirements increase with decreased precipitation. For instance, Rwanda, the smallest of
Figure 2. Increase in annual average yields over ten years (2010–2019) of simulated crop growth for improved cultivars grown with low soil fertility. The maps measure the yield increase from rainfed to irrigated crops in metric tons of fresh weight per hectare (t ha$^{-1}$). Note that the scale of the color scheme differs between crops. Negative change or incomplete growth indicates a negative difference between rainfed and irrigated crop growth or not fully developed canopies.
Figure 3. Annual average water demand for irrigation over ten years (2010–2019) of simulated crop growth for improved cultivars grown with low soil fertility. The maps measure net irrigation requirements in millimeters per additional metric ton (mm t\(^{-1}\)) of fresh weight. Note that the scale of the color scheme differs between crops. Negative change or incomplete growth indicates a negative difference between rainfed and irrigated crop growth or not fully developed canopies.
Figure 4. Annual average electricity demand for irrigation over ten years (2010–2019) of simulated crop growth for improved cultivars grown with low soil fertility. The maps measure electricity for irrigation in kilowatt-hours per additional metric ton ($\text{kWh t}^{-1}$) of fresh weight. Note that the scale of the color scheme differs between crops. The geographical scale of each country’s map is different for better appreciation.
Figure 5. Levelized cost of irrigation (LCOI) for 690 woredas in Ethiopia, 30 districts in Rwanda, and 80 districts in Uganda. There is one dot per district-crop-cultivar-fertility level combination. The vertical axis on the left shows the four fertility levels: low, medium, near-optimal, and non-limiting. The horizontal axis shows the present value of the irrigation system's costs per additional ton due to irrigation. The black vertical dashed lines represent (from left to right) the minimum, mean, and maximum annual crop price in US$ per ton (FAO 2021) from 2010 to 2019.
the countries in this study with more homogeneous meteorological conditions, has the smallest range of electricity requirements per ton. The other factor that is directly proportional to electricity demand is the depth to groundwater tables. Along with poor soil’s water drainage characteristics and higher rainfall variability, Ethiopia’s and Uganda’s largest distances to groundwater explain the higher electricity demands for irrigation than Rwanda’s.

3.2. LCOI
Comparing a given crop’s LCOI and market price can provide an idea of the economic viability of irrigating a crop. Figure 5 shows the LCOI estimates for all districts in a country under different soil fertility levels and low- and high-yield cultivars. By plotting the present value of all the simulation results in each country, figure 5 emphasizes the variability and uncertainty in our simulation results. The figure also includes a range of observed farm gate crop prices between 2009 and 2019, described in more detail in the SI. This figure highlights that irrigation may only be viable for horticulture crops. However, soil fertility level is a primary limiting factor. In the low fertility simulations, irrigation is not viable even for horticulture crops, which suggests that fertilizer application may be needed in addition to irrigation. It is worth noting that crop prices for maize, onion, and tomato are substantially lower in Ethiopia than in Rwanda and Uganda. It is possible that higher yields from irrigation could drive down crop prices as domestic production increases.

On the other hand, crop prices in East African countries may be artificially low because of food, aid, or imports from other countries’ subsidized crops (USDA-FAS 2021). For instance, according to the FAO, Rwanda’s wheat production in 2019 totaled close to 16 000 tonnes, while commercial imports from Europe and North America totaled 160 000 tonnes (FAO 2021). Similarly, commercial imports of maize in Rwanda in 2019 were equivalent to 18% of domestic production (FAO 2021). However, most of these imports came from other countries in SSA, where agricultural subsidies may be less prevalent than in North America and Europe (FAO 2021). In Uganda, commercial wheat imports from Europe, North America, and South America totaled 425 000 tonnes, while domestic production totaled 24 000 tonnes in 2019 (FAO 2021). Finally, in Ethiopia, commercial wheat imports in 2019 equaled 1460 000 tonnes (FAO 2021) (the equivalent of about 25% of domestic production), with a significant share coming through food aid programs (USDA-FAS 2021). Additional productivity through investments in irrigation could thus reduce reliance on international aid and decrease trade deficits.

Adding post-harvest activities along the crop’s value chain (e.g. processing maize for flour production) can help accommodate increased production, likely boosting irrigation systems’ profitability. Finally, the cultivar or seed variety may not influence the irrigation’s financial viability as much as the fertility level and seems to be more country-specific.

3.3. Productivity and food security
Figure 5 in the previous section showed irrigation-driven changes in annual yields derived from simulations over ten years. Variability in agricultural productivity poses risks to food security in East Africa, with countries facing famine conditions in years with low yields (Hasell and Roser 2013). Irrigation can improve food security by increasing yields and reducing the interannual variability of yields (Darko et al 2015), particularly during the dry season (Burney et al 2010). Indeed, figure 6 shows the average annual yields per country across all districts for the different crops and fertility levels. The figure highlights that pressurized irrigation can stabilize yields (reduce variability) for staple and horticulture.
Figure 7. Techno-economic feasibility analysis for improved cultivars grown with non-limiting soil fertility. A district is techno-economically feasible when its LCOI (y-axis) is lower than a given crop price, and the groundwater availability (x-axis) (i.e. recharge minus irrigation) is positive. The row under each country’s maps shows the 2019 crop price in current US$ per tonne (FAO 2021). In general (except for very low crop prices), purple-colored districts are viable, while yellow- and green-colored districts are unfeasible.
3.4. Sensitivity analysis: improving soil fertility

As noted earlier, low soil fertility levels may limit the benefits of irrigation, and expanded use of fertilizers may complement investments in irrigation infrastructure. In this section, we present the analysis of a scenario in which soil fertility is non-limiting. We use the LCOI and the hydrology model to define techno-economic feasibility. A district is techno-economically feasible when the LCOI is lower than the crop price and the groundwater availability (i.e. recharge minus irrigation) is positive. Figure 7 shows that, for crops grown with improved cultivars and non-limiting soil fertility, the highest techno-economic feasibility occurs for horticulture crops in districts of Ethiopia’s Central-Western, most of Rwanda’s Western half, and Uganda’s Southeastern and Northwestern. This figure also highlights that potato is the staple with a higher proportion of techno-economically feasible districts. In general, purple-colored districts are viable, while yellow- and green-colored districts are unfeasible. With limited capital, decision-makers may deem it wise to prioritize high-feasibility areas first.

We find that the techno-economic feasibility range across cultivars and fertility levels is 17%–36% in Ethiopia, 19%–67% in Rwanda, and 14%–45% in Uganda. This range indicates the proportion of techno-economically feasible districts, with the lower value showing traditional cultivars grown with low fertility and the higher value improved cultivars grown with non-limiting fertility. These results suggest that Rwanda has the highest irrigation feasibility. However, Rwanda is a much smaller country, and there may be sub-regions in Uganda and Ethiopia...
with high irrigation feasibility. Moreover, finding an irrigation system’s profitability requires a more comprehensive analysis, including, but not limited to, fertilizer costs, local crop prices (dependent on regional supply and demand), labor wages, and even specific cultivars’ growth patterns.

As noted earlier, we performed a sensitivity analysis to evaluate the effect of electricity prices on the LCOI. Figure 8 shows the LCOI changes with respect to the baseline (0.5 US$ kWh$^{-1}$) for low (0.1 US$ kWh$^{-1}$) and high (1.0 US$ kWh$^{-1}$) electricity prices. These prices are indicative of on-grid and off-grid sources, respectively. The figure highlights that the crops grown in Ethiopia have the highest LCOI change, followed by Uganda and then Rwanda. We find that Ethiopian tomato is the most sensitive to changes in electricity prices. More information about LCOI changes on a country level is available in the SI. Meanwhile, changes in electricity prices have negligible effects on the irrigation techno-economic feasibility of horticulture crops grown with moderate (or higher) soil fertility levels and considerable effects on staples grown in soils with near-optimal (or lower) fertility.

4. Conclusions

Our study shows that small-scale pressurized irrigation can improve yields for staple and horticulture crops in Ethiopia, Rwanda, and Uganda. However, our results suggest that the investments in agriculture may only be financially viable for horticulture crops. On the other hand, even for staple crops, irrigation investments could improve food security in the region by reducing the interannual variability in yields, reduce reliance on food aid, and potentially reduce trade deficits. Our results further highlight that soil quality can limit the benefits associated with investments in irrigation. Thus, increased fertilizer use may complement investments in irrigation infrastructure. These results are consistent with Sheahan and Barret’s (2017) findings, which point out the economic benefits of combining irrigation, improved seeds, and fertilizers. While there is a growing availability of high-yield cultivars, soil quality is a primary driver of our results. Only the simulations for potato suggest that the type of cultivar influences the value of irrigation investments, likely because potatoes are not as sensitive to soil fertility levels as other crops.

The simulation results show that the techno-economic feasibility is spatially heterogeneous across districts and dependent on climate zone, fertility, water availability, crop type, and crop prices. For instance, parts of Southwestern Ethiopia with large desert regions seem less suitable for planting crops due to far-off or insufficient water resources. The techno-economic feasibility of irrigating staple crops is strongly dependent on soil fertility. The crop market price can influence irrigation’s economic viability, especially for staple crops. Changes in electricity prices can significantly change the LCOI. It is unlikely that at low artificial fertilizer inputs, any investments will have attractive economic returns. Therefore, fertility and irrigation may be equally important in East Africa for boosting primary production.

Pressurized irrigation can help ensure food security and achieve levels of agricultural modernization through electricity access and steady consumption patterns towards reaching the end goal of universal electrification. An analysis of the aggregated productivity potential per district in currently planted areas (IFPRI 2020) yielded projected electricity for irrigation demands of 1.6 TWh in Ethiopia, 490 GWh in Rwanda, and 670 GWh in Uganda. These values represent 17%, 65%, and 17% of the current electricity demand in these countries, respectively (IEA 2018, NISR 2018, UBOS 2020a).

In considering the results of this work, it is essential to acknowledge its limitations. For instance, incorporating additional productive uses of electricity along agricultural value chains (e.g. post-harvest processing, packaging, storage) could increase investment returns. However, other water uses beyond irrigation could increase competition for a finite resource and be detrimental to agricultural productivity. Competing water uses might include potable water supply for human use, produce washing, and even power generation. Under a future changing climate, irrigation needs may change. Admittedly, our analysis does not intend to predict future productivity or resource requirements, nor does it attempt to forecast the impact of irrigation on individual years with extreme conditions (e.g. rainy, dry, or hot). Any analysis aiming to answer those questions is out of our study’s scope and would likely require extensive calibration of relevant parameters, such as climate data or crop physiology. Instead, our study intends to provide quantitative-based insights to inform decision-making and planning in places where infrastructure might not yet be fully developed or adequate. A more extensive description of the limitation of this work is available in the SI.

The results of this study aim to assist decision-makers in identifying areas of high potential for coordinated investment in electricity and irrigation infrastructure to improve agricultural productivity and the financial sustainability of rural electrification in East Africa with electricity-powered pumped irrigation. Future work includes a detailed analysis of the benefits of irrigation and electricity infrastructure to electric utilities. Other possible areas for further exploration include evaluating opportunities from growing high-value crops and adding post-harvest activities to the electricity load. Our results highlight, however, that irrigation investments and increased
fertilizer use are complementary to improving agricultural productivity and food security.

**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.5082395.

**Acknowledgments**

Funding for this project came from the Rockefeller Foundation. We thank Vijay Modi from Columbia University for providing insightful feedback to do our simulations. This paper’s results and conclusions are the authors’ sole responsibility and do not represent the funding sources’ views.

**ORCID iDs**

Jorge L Izar-Tenorio @ https://orcid.org/0000-0001-9219-5500
Paulina Jaramillo @ https://orcid.org/0000-0002-4214-1106
Nathan Williams @ https://orcid.org/0000-0002-5676-2288

**References**

Akumaga U, Tarhule A and Yusuf A A 2017 Validation and testing of the FAO AquaCrop model under different levels of nitrogen fertilizer on rainy season maize in Nigeria, West Africa Agric. For. Meteorol. 232 225–34
Alley W M 1984 On the treatment of evapotranspiration, soil moisture accounting, and aquifer recharge in monthly water balance models Water Resour. Res. 20 1137–49
Andarzian B, Bannayan M, Mazraeh H, Barati M E, Barati M A and Rahnama A 2011 Validation and testing of the AquaCrop model under full and deficit irrigated wheat production in Iran Agric. Water Manage. 101 1–8
Araya A, Keestra S D and Stroosnijder L 2010 Simulating yield response to water of Tef (Eragrostis tef) with FAO’s AquaCrop model Field Crops Res. 116 196–204
Banerjee S G, Malik K, Tipping A, Besnard J and Nash J 2017 Double dividend: power and agriculture nexus in sub-Saharan Africa (World Bank Group Report)
Burney J, Woltering L, Burke M, Naylor R and Pasternak D 2010 Solar-powered drip irrigation enhances food security in the Sudano-Sahel Proc. Natl Acad. Sci. USA 107 1848–53
Calvis K and Fisher-Vanden K 2017 Quantifying the indirect impacts of climate on agriculture: an inter-method comparison Environ. Res. Lett. 12 115004
Campana P E, Li H and Yan J 2015 Techno-economic feasibility of the irrigation system for the grassland and farmland conservation in China: photosynthetic vs. wind power water pumping Energy Convers. Manage. 103 311–20
Chaudhary J N, Shabbir G, Ahmed S and Waqas A 2017 Chapter 13: pressurized irrigation systems Applied Irrigation Engineering ed A Bakhsh and M R Choudhry (Faisalabad: University of Agriculture)
Chavarria G and dos Santos H P 2012 Plant water relations: absorption, transport, and control mechanisms Advances in Selected Plant Physiology Aspects ed G Montanaro and B Diao (London: IntechOpen) (https://doi.org/10.5772/35478)
Cooley H and Phurisamphan R 2016 The cost of alternative water supply and efficiency options in California (Pacific Institute) (available at: https://pacinst.org/wp-content/uploads/2016/10/Pi_TheCostOfAlternativeWaterSupplyEfficiencyOptionsinCA.pdf)
Cornish G A 1998 Pressurised irrigation technologies for smallholders in developing countries—a review Irrig. Drain. Syst. 12 185–201
Darío R O, Yuan S, Hong L, Liu J P and Yan H 2015 Irrigation, a productive tool for food security—a review Acta Agric. Scand. B 66 191–206
Darío R O, Yuan S, Yan H F, Liu J P and Abbey A 2016 Calibration and validation of AquaCrop for deficit and full irrigation of tomato Int. J. Agric. Biol. Eng. 9 104–10
Duke H R 2007 Chapter 12: pumping systems Design and Operation of Farm Irrigation Systems 2nd edn (St. Joseph, MI: American Society of Agricultural and Biological Engineers) pp 392–425
FAO (Food and Agriculture Organization of the United Nations) 2021 FAOSTAT database (Rome: FAO) (available at: www.fao.org/faostat/en/#data)
FAO/IIASA/ISRIC/ISSCAS/JRC 2012 Harmonized world soil database (version 1.2) FAO, Rome, Italy and HASA, Lausen, Austria
FEWS NET (Famine Early Warning Systems Network) East Africa food security outlook June 2021 to January 2022 [Online resource]. Published online at fews.net (available at: https://fews.net/sites/default/files/documents/reports/east-africa-key-messages-202107-final.pdf)
Fipps 2017 Calculating horsepower requirements and sizing irrigation supply pipelines Texas Agricultural Extension Service B-6011 (available at: https://aglifesciences.tamu.edu/baen/wp-content/uploads/sites/24/2017/01/B-6011-Calculating-Horsepower-Requirements-and-Sizing-Irrigation-Supply-Pipelines.pdf)
Geankoplis J C 1998 Capítulo 4. Principios de transferencia de calor en estado estacionario (Ediciones Mc Graw-Hill, México) pp 1008
Giordano M, de Fraiture C, Weight E and van der Bliek J 2012 Water for wealth and food security: supporting farmer-driven investments in agricultural water management. Synthesis report of the AgWater Solutions Project. Colombo, Sri Lanka: International Water Management Institute (IWMI) p 50
Hasell J and Roser M 2013 Famines. [Online resource]. Published online at OurWorldInData.org (available at: https://ourworldindata.org/famines)
Hendriksen K and Hansen S L 2001 Increasing the dry matter production in bulb onions (Allium cepa L.) Acta Hortic. 555 147–52
IEA (International Energy Agency) 2018 Ethiopia country profile (Paris: IEA) (available at: www.iea.org/countries/ethiopia)
IPFRI (International Food Policy Research Institute) 2020 Spatially disaggregated crop production statistics data in Africa South of the Sahara for 2017 Harvard Dataverse, V2
Izar-Tenorio J, Jaramillo P and Williams N 2021 Techno-economic feasibility of small-scale pressurized irrigation in Ethiopia, Rwanda, and Uganda through an integrated modeling approach (version 2.0) (https://doi.org/10.5281/zenodo.5082395)
Katerji N, Campi P and Mastrorilli M 2013 Productivity, evapotranspiration, and water use efficiency of corn and tomato crops simulated by AquaCrop under contrasting water stress conditions in the Mediterranean region Agric. Water Manage. 130 14–26
Kay M 2001 Smallholder Irrigation Technology: Prospects for sub-Saharan Africa (Rome: International Program for Technology and Research in Irrigation and Drainage (IPTRID))
Lambers H and Oliveira R S 2019 Plant water relations Plant Physiological Ecology (Berlin: Springer)
MacDonald A M, Honson H C, Dochartaigh B É Ó and Taylor R G 2012 Quantitative maps of groundwater resources in Africa Environ. Res. Lett. 7 024009

Magalhães I D et al 2019 Performance of the AquaCrop model for bean (Phaseolus vulgaris L.) under irrigation condition Aust. J. Crop Sci. 13 1188–96

Montoya F, Camargo D, Ortega J F, Corcoles J I and Dominguez A 2016 Evaluation of Aquacrop model for a potato crop under different irrigation conditions Agric. Water Manage. 164 267–80

Mwamakamba S N, Sibanda I M, Pittick J, Stirzaker R, Bjornlund H, van Rooyen A, Munguambwe P, Mdemu M V and Kashaiilig I J 2017 Irrigating Africa: policy barriers and opportunities for enhanced productivity of smallholder farmers Int. J. Water Resour. Dev. 33 824–38

NISR (National Institute of Statistics of Rwanda) 2018 Energy Statistics, 2017. Dataset (available at: http://statistics.gov.rw/publication/energy-statistics-2017)

NISR (National Institute of Statistics of Rwanda) 2020 Seasonal agricultural survey (SAS) annual report 2019 (available at: www.statistics.gov.rw/publication/seasonal-agricultural-survey-2019-annual-report)

Nordhaus T, de Kirby K, Beek T, Brush E and Trembath A 2019 The road more traveled: cases in universal electrification The Breakthrough Institute, 2019

Ondricek I, Komendantova N and Patt A 2013 WACC the dog: NISR (National Institute of Statistics of Rwanda) 2018 Energy Statistics, 2017. Dataset (available at: http://statistics.gov.rw/publication/energy-statistics-2017)

Ondricek I, Komendantova N and Patt A 2013 WACC the dog: NISR (National Institute of Statistics of Rwanda) 2018 Energy Statistics, 2017. Dataset (available at: http://statistics.gov.rw/publication/energy-statistics-2017)

Perez – Orotola M, Daccache A, Hess T M and Knox J W 2015 Simulating impacts of irrigation heterogeneity on onion (Allium cepa L.) yield in a humid climate Irrig. Sci. 33 1–14

Raes D 2017 AquaCrop training handbook I. Understanding AquaCrop (Rome: Food and Agriculture Organization of the United Nations) (available at: www.fao.org/3/a-i6051e.pdf)

Raes D, Steduto P, Hisao T C and Fereres E 2018 Annexes, AquaCrop version 6.0–6.1. Reference manual (Rome: Food and Agriculture Organization of the United Nations) (available at: www.fao.org/3/BR244E/br244e.pdf)

Reid K 2021 Africa hunger, famine: facts, FAQs, and how to help. [Online resource]. Published online at WorldVision.org (available at: www.worldvision.org/hunger-news-stories/africa-hunger-famine-facts)

Rodríguez-Huerta E, Rosas-Casals M and Hernández-Terones I M 2020 A water balance model to estimate climate change impact on groundwater recharge in Yucatan Peninsula, Mexico Hydrof. Sci. J. 65 470–86

Rosegrant M, Ringler C and de Jong I 2009 Irrigation: tapping agricultural inputs use in sub-Saharan Africa Agric. Water Manage. 129 9–20 plan Tender Number 021/RNRA/2011–2012. Master Plan Report: Main Volume. Rwanda Natural Resources Authority (available at: https://environnement.gov.ro/ uploads/media/Rwanda_Water_Resources_Master_Plan_01.pdf)

Siebert S, Burke J, Fares J M, Frenken K, Hoogeveen J, Döll P and Portmann F T 2010 Groundwater use for irrigation—a global inventory Hydrol. Earth Syst. Sci. 14 1863–80

Stackhouse P 2019 POWER data methodology (available at: http://power.larc.nasa.gov)

Steduto P, Hisao T C, Fereres E and Raes D 2012 Crop yield response to water, EAO irrigation and drainage Paper No. 66 (Rome: Food and Agriculture Organization of the United Nations)

Steduto P, Hisao T C, Raes D and Fereres E 2009 AquaCrop—the FAO crop model to simulate yield response to water: I. Concepts and underlying principles Agron. J. 101 426–37

Swendsen S, Ewing M and Msangi S 2009 Measuring irrigation performance in Africa IFPRI Discussion Paper 894 (Washington, DC: International Food Policy Research Institute)

UBOS (Uganda Bureau of Statistics) 2010 Uganda census of agriculture 2008/2009. Volume IV: crop area and production report (available at: www.ubos.org/wp-content/uploads/publications/03_2018/UCACrop.pdf)

UBOS (Uganda Bureau of Statistics) 2020a 2019 Statistical abstract (available at: www.ubos.org/wp-content/uploads/publications/06_2020AAS_2018_Report_Final_050620.pdf)

USDA-FAS (United States Department of Agriculture—Foreign Agricultural Service) 2021 Grain and feed annual, Ethiopia. Global agricultural information network (available at: https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Grain%20and%20Feed%20Annual_Addis%20Ababa_Ethiopia_03-15-2021)

Waldhoff S T, Wing I S, Edmonds J, Leng G and Zhang X 2020 Future climate impacts on global agricultural yields over the 21st century Environ. Res. Lett. 15 114010

World Bank 2017 World development indicators Fertilizer consumption (kilograms per hectare of arable land) [Data file] (available at: https://data.worldbank.org/indicator/NY.GDP.PCAP.CD) USDA-FAS (United States Department of Agriculture—Foreign Agricultural Service) 2021 Grain and feed annual, Ethiopia. Global agricultural information network (available at: https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Grain%20and%20Feed%20Annual_Addis%20Ababa_Ethiopia_03-15-2021)

World Bank 2021b World development indicators GDP per capita (current US$) [Data file] (available at: https://data.worldbank.org/indicator/NY.GDP.PCAP.CD) USDA-FAS (United States Department of Agriculture—Foreign Agricultural Service) 2021 Grain and feed annual, Ethiopia. Global agricultural information network (available at: https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Grain%20and%20Feed%20Annual_Addis%20Ababa_Ethiopia_03-15-2021)

World Bank 2021b World development indicators Population density (people per sq. km of land area) [Data file] (available at: https://data.worldbank.org/indicator/EN.POP.DNST)

You L, Ringler C, Wood-Sichra U, Robertson R, Wood S, Zhu T, Nelson G, Guo Z and Sun Y 2013 What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach Food Policy 36 770–82

Yuan M, Zhang L, Gou F, Su Z, Spiertz J H J and van der Werf W 2017 Quantitative maps of groundwater resources in Africa Rwanda Natural Resources Authority (available at: https://environnement.gov.ro/uploads/media/Rwanda_Water_Resources_MASTER_Plan_01.pdf)

Zhai H and Rubin E 2013 Techno-economic assessment of polymer membrane systems for postcombustion carbon capture at coal-fired power plants Environ. Sci. Technol. 47 3006–14

Zou X, Li Y, Cremades R, Gao Q, Wan Y and Qin X 2013 Assessment of crop growth and water productivity for five C3 species in semi-arid inner Mongolia Agric. Water Manage. 122 28–38

Zhao H and Rubin E 2013 Techno-economic assessment of polymer membrane systems for postcombustion carbon capture at coal-fired power plants Environ. Sci. Technol. 47 3006–14

Zou X, Li Y, Cremades R, Gao Q, Wan Y and Qin X 2013 Assessment of crop growth and water productivity for five C3 species in semi-arid inner Mongolia Agric. Water Manage. 122 28–38