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PERSPECTIVE

Economics of sustainable irrigation in smallholder agriculture: implications for food security and climate action

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1. Poor understanding of irrigation systems, services, and economics hinders progress on food security, climate action, and nature conservation

Irrigation is crucial for food systems transitions, contributing to food security, climate change mitigation and adaptation, and poverty reduction (Rosa 2022, McDermid *et al* 2023). Similarly, population growth, economic development, and climate change exacerbate physical and economic water scarcity, requiring concerted efforts for agricultural water use to stay within sustainable boundaries (de Graaf *et al* 2019, Hendriks *et al* 2023, Mehta *et al* 2024). Consequently, sustainable irrigation—i.e. irrigation for healthy food production through fair water use within planetary boundaries—is (re)emerging as an important field of study. Sustainable irrigation aims to understand how, when, and where to bring water systems and agricultural systems *in balance*—i.e. harmonise water use for food security, economic development, and environmental sustainability. This includes estimating changing crop water requirements, water availability, earth system feedbacks, and low-emission irrigation strategies (Jain *et al* 2021, Vereecken *et al* 2022, Yuan *et al* 2024). However, defining context-specific goals and navigating transitions remains insufficiently considered, with inadequate attention paid to social, technological, ecological, institutional, and economic factors that often make irrigation transitions difficult to achieve in practice.

Importantly, the idea of water as a human right that is freely available to all conceals the actual economic cost many farmers incur for delivering water. These can range from a few dollars up to $200+ per season. To address this, this (re)emerging field of sustainable irrigation can build on international policy recommendations for valuing water, such as the Mar del Plata conference (UN 1977), the Dublin Principles (WMO 1992), the High-Level Panel on Water (HLPW 2018), the UN Valuing Water Initiative, and the Bellagio principles (HLPW 2017). Although formerly focusing on the productive value of water, these policy initiatives now embrace a stronger focus on inclusivity, multiple water users, and ecosystem services and allow for a common platform to discuss, envision, and plan for sustainable irrigation systems. However, these previous policy and research initiatives have not yet systematically collected data on irrigation systems and water cost globally nor analysed how irrigation economics can inform policy or program design to achieve sustainability goals across regions.

Here, we argue that a more substantial focus on the economics of water delivery and its human and natural drivers is required to inform sustainable irrigation discussions and move the needle on reaching global challenges such as zero hunger, poverty reduction, clean water for all, and climate action.

2. Towards a systems framework for irrigation water delivery in the food and earth system

Sustainable irrigation diverts water from natural or semi-natural sources to farmers' fields for climate

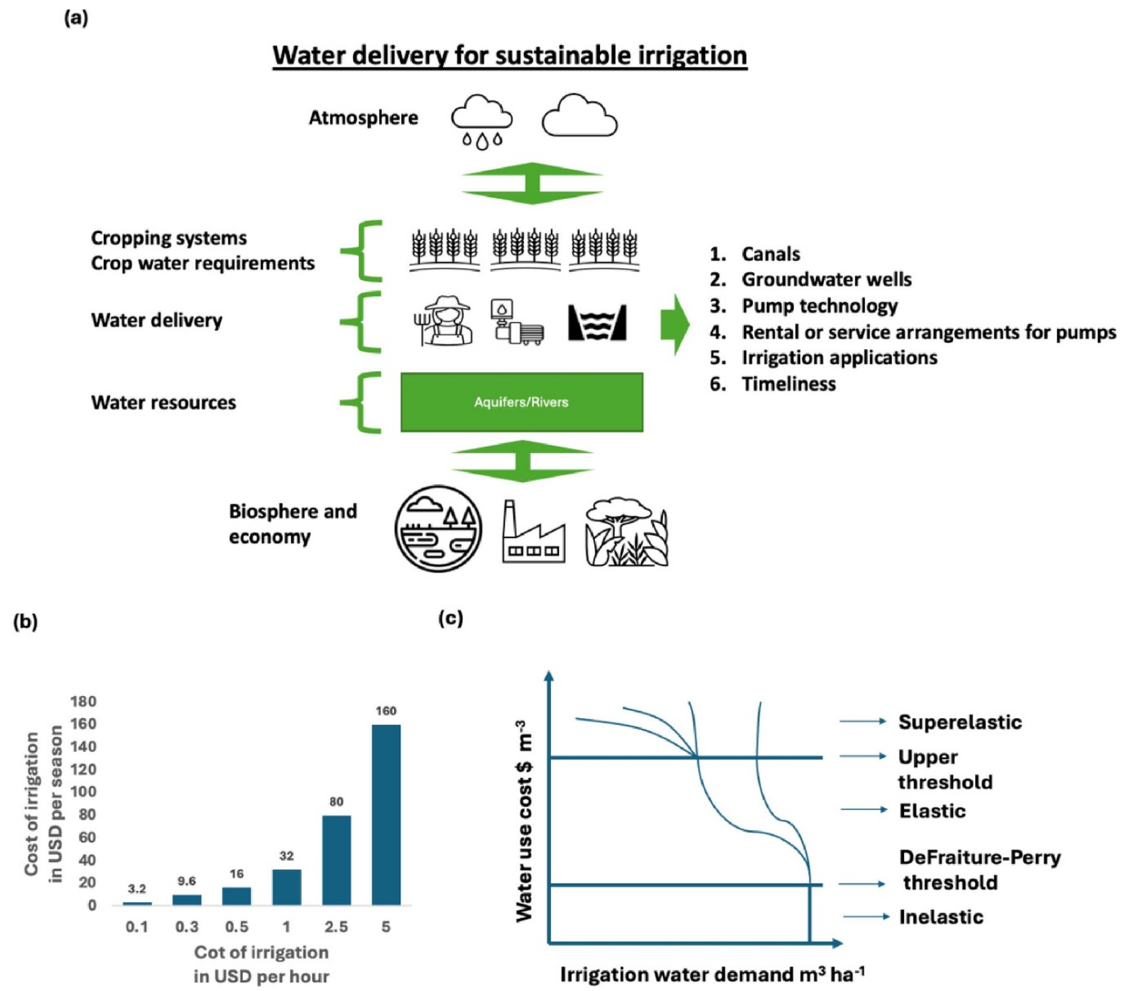

Figure 1. (a): Overview of role irrigation water delivery systems as a link between agriculture and water resources. (b): Example of typical water pumping costs for different hourly rates for a smallholder plot and its impact on the full cost of irrigating this plot for a duration of 8 h on 4 d in a season. (c) Shah *et al* (2009) conceptual overview of irrigation water use response to different water costs.

resilient and productive agriculture—impacting food and earth systems (figure 1). These impacts extend beyond food security to non-agricultural ecosystems and various users and include feedbacks with the atmosphere that can cool ambient temperature, affect rainfall, and contribute to GHG emissions. A large literature exists on volumetric water pricing, changing electric tariffs or power availability, and designing grid connected solar power systems to encourage sustainable irrigation use (De Fraiture & Perry, 2022, Sidhu *et al* 2020). But solutions remain difficult to implement as, e.g. politically feasible fees are too low to make a meaningful impact on farmers' water use decisions and expensive pump rentals encourage only protective irrigation (Shah *et al* 2009).

In global science-policy fora, such as the Intergovernmental Panel on Climate Change (IPCC), irrigation is identified as a foundational adaptation option for addressing progressive climate change and climate extremes. Especially in much of Sub-Saharan Africa or Asia, increasing water use in agriculture is a non-negotiable adaptation option and can drive sustainable intensification of agriculture (Yuan *et al* 2024). Nevertheless, irrigation may prove maladaptive if it depletes fossil aquifers or disrupts ecological flows. This begs the question: How can irrigation be leveraged for sustainably producing a healthy diet while balancing its impact on the climate system, the environment, and ensuring inclusivity?

So—what is needed? Many such questions come down to costs and irrigation systems—and these vary widely. Capital investments range from \$100 for a small pump to >\$100 m for a canal project. Farm scale operating costs range from \$0 to \$5 per hour (table 1). In addition, some countries such as Chile, Australia and the United States develop water markets for trading water rights but these are not easily implementable in smallholder contexts (Garrick *et al* 2023). The most crucial aspects of sustainable irrigation economics in smallholder environments can be easily captured in agronomic or other food system surveys through the following aspects:

1. **Water sources**: groundwater or surface water; year-round availability; canals and/or pumps;
2. **Canals**: fees area^{-1} season^{-1} or yr^{-1}; in-kind fees;
3. **Groundwater wells**: capital cost; depth; diameter
4. **Pump technology**: capital costs; power source; HP; year purchased; repair costs, operating costs h^{-1}; rented or owned; service/rent to others + number;
5. **Rental or service arrangements for pumps**: own labour or service; hourly vs. season^{-1} per area^{-1}; fee or rate;
6. **Irrigation practice**: number of irrigations; average hours per irrigation; irrigated crop stages;
7. **Timeliness**: on time?; days of delay; delay factors (e.g. canal turn, canal maintenance, pump availability, electricity availability, financial liquidity, pump repairs);
8. **Crops**: crop grown; sowing date; harvest date; yield

Lastly, mapping irrigation systems, costs, and how these affect sustainable irrigation practices also need to consider farmers' livelihoods. Most smallholder farms are too small to make a living income and agriculture only comprises a small portion of their livelihood portfolio (Frelat *et al* 2016, Urfels *et al* 2023). As a result, irrigation and other farm management decisions are not necessarily driven by farm economics but also by off-farm income, labour markets, and migration.

3. Mini case studies from across Asia

This section provides an overview of field reports of typical irrigation practices and costs based on based on the author's discussions with farmers and water managers during project activities that extend across several districts of the case study regions and preliminary surveys and project documents from ongoing projects between 2023 and 2024. These mini case studies are thus only indicative and not necessarily representative of the entire regions. The purpose of these field reports is to sketch an initial overview of the diversity of irrigation economics across and within regions that we argue should be further consolidated with more robust data collection and analytics.

Northwest India is a global groundwater depletion hotspot with declining water tables 0.33 m yr^{-1} due to subsidised submersible pumps and electricity. Canal fees range from \$0.52 ha^{-1} to \$1.19^{-1} season^{-1} and are sometimes charged at \$4.52 ha^{-1} yr^{-1}. As such, water delivery in this region has been virtually free for several decades and is associated with environmental degradation including air pollution and biodiversity loss, despite efforts to address the overuse of water.

In the Eastern Gangetic Plains of Nepal and India, inadequate electricity networks and canals have farmers rely on diesel pumps and shallow groundwater wells—paying \$0.5–1.5 h^{-1} operating cost and up to \$5 h^{-1} for rentals—resulting in low yields despite abundant water resources. Recognizing this issue, governments invest in electric grids but may risk recreating the Northwests' depletion issues. Still, these transitions to electric pumps do not precipitate quick change in rental rates which only settle at ∼\$1.5 h^{-1} after several years—still much higher than the \$0.05–0.2 h^{-1} operating costs.

Table 1. Overview of typical irrigation costs across countries based on the author's discussions with farmers and water managers in ongoing project activities and preliminary survey results. This table is indicative, and we present it to provide an initial overview that demonstrates the insights that can be provided with more robust and representative data available at scale. '≈' indicates estimates if hourly or seasonal rate was missing and is based on calculation as per figure 1(b) for typical cereal crop irrigation schedules.

	Canal fees	Agricultural electricity fee	Diesel pumping cost	Pump rental price	Surface vs. Groundwater irrigation (%)
Northwest India	\$0.52–4.52 ha^{-1} season^{-1}	Free or heavily subsidised, flat rates	\$1.10 h^{-1} ≈ \$35.1 season^{-1}	Uncommon	20:80
Eastern India	\$2.16–4.4 ha^{-1} season^{-1}	\$0.06–0.15 h^{-1} ≈ \$1.9–4.5 season^{-1}	US\$0.6–1.10 h^{-1} ≈ \$19-35 season^{-1}	\$1.50–4.50 h^{-1} ≈\$48–144 ha^{-1} season^{-1}	10:90
Philippines	Free; if agricultural area is below 8 ha;	\$0.15–0.35 h^{-1} ≈\$4.8–11.2 season^{-1}	\$1.05–1.16 h^{-1} ≈\$33–37 season^{-1}	\$2.12–3.35 h^{-1} plus diesel ≈\$100–139 ha^{-1} season^{-1}	60:40
Indonesia	\$4.16–10.2 ha^{-1} yr^{-1}; plus pumping cost	\$0.05–0.09 h^{-1} ≈ \$1.6–2.8 season^{-1}	≈\$1.6–2.0 h^{-1} \$22–96 ha^{-1} season^{-1}	≈\$2 h^{-1} \$64 ha^{-1} season^{-1}	65:35
Sri Lanka*	Free;	\$0.05–0.3 h^{-1} ≈\$1.6–9.6 season^{-1}	≈\$0.9-2 h^{-1} 95 ha^{-1} season^{-1}	N/A	N/A
Cambodia	\$12.50 ha^{-1} yr^{-1} plus pumping costs	\$0.1–0.15 h^{-1} ≈\$3.2–4.8 season^{-1}	\$1.13 h^{-1} \$54-64 ha^{-1} season^{-1}	Uncommon; cost of diesel only	95:5
Nepal	\$1 – 5.12 ha^{-1} yr^{-1}	\$0–0.09 h^{-1} ≈\$0–2.9 season^{-1}	\$1.17 h^{-1} ≈\$37 ha^{-1} season^{-1}	\$2.26–4.56 h^{-1} ≈\$72–146 ha^{-1} season^{-1}	60:40

In Sri Lanka, irrigation focuses on canal irrigated rice in inland valleys with typical tank systems for water storage that are generally free of charge to farmers. For crops other than rice especially in the dry season and outside canal irrigation systems, groundwater use is common and typical fuel rates for pumping are set per season amounting to \$95 ha^{-1} season^{-1}. A substantial amount considering a typical \$100 profit margin in many low-income countries for cereal production.

In the Philippines, canal and groundwater are both used and since 2017 all canal irrigation fees have been abolished. However, many people have access to groundwater with hourly electricity or diesel rates at \$0.15–1.5 h^{-1} and use it outside canal command areas, at the tail ends of the canals, or within the central part of the command area in times of drought or canal maintenance. Farmers also rent their pumps charging \$2.12–3.32 h^{-1} excluding the ca. \$1.05 h^{-1} diesel cost.

In central Java, Indonesia farmers pay ca. \$0.05–2 h^{-1}— amounting to ca. \$16-28 ha^{-1} season^{-1} for electricity and \$22-96 ha^{-1} season^{-1} for diesel. Pump rentals in central Java are charged at ca. \$1.92 h^{-1}. Within Cambodia, in Takeo and Prey Veng, water pumping and canal fees are similar to Indonesia, but reports of groundwater pump rentals are scarce. In both countries farmers pump canal water by themselves or through rentals. So the plot's distance from canals becomes an important factor for irrigation costs and affects whether groundwater or surface water is more economical.

Similarly, in Vietnam's Mekong Delta water is pumped by farmers or irrigation pumping corporations from main canals to lower-level canals and tertiary canals that lead to farmers' fields with varying official electricity charges which are normally waived and thus essentially free as well. Groundwater irrigation does occur, but increasingly policies restrict the use of groundwater for irrigation due to sustainability concerns.

4. A research and policy agenda

As shown in section 3, the economics of sustainable irrigation delivery vary widely across different parts of Asia. Better understanding and accounting for these can help to address the following challenges:

(i) incentivize reduction of water consumption in areas of depletion
(ii) encourage equitable and sustainable increase in irrigation where warranted
(iii) reduce farmers' irrigation costs where they are too high
(iv) improve drought-risk preparedness planning
(v) encourage low-emission rice irrigation schedules.

To address the above, three interlinked research areas can generate robust and context-specific evidence for investing in sustainable irrigation configurations and institutional mechanisms for climate resilient agricultural production that is healthy for people and the planet.

1. First, the problem definition of sustainable water use in agriculture under a changing climate needs improvement in most major food bowls. Many water problems are wicked problems, but more clarity and quantification of impacts is needed for research and policy programs. Narrowly-construed technological or management options such as *drip irrigation* or *crop diversification* are often pursued to address *water problems* with limited and often unintended results. More evidence-driven, scientifically informed, and logically consistent theories of change are needed that honour both bio-physical and socioeconomic contexts. Transdisciplinary efforts are needed to co-develop this evidence-base and improve local and regional frameworks for sustainable water use.
2. Second, mapping actual irrigation water use, water delivery technologies, and the costs farmers pay for them and how this affects agricultural and livelihood outcomes is crucial. Insufficient data exists on these topics and research initiatives on water and agricultural scientists must do more to address this to avoid irrigation practices flying under the radar of decision-makers and researchers (Venot *et al* 2021). R4D initiatives are increasingly collecting large-scale data through LCAS, RHoMIS, Baseline Surveys (Hammond *et al* 2017, Vanlauwe and Casimero 2021, McDonald *et al* 2023). Explicitly focusing on and integrating a stronger irrigation module can help to substantially improve this field. We provide a sample lean irrigation module on the LCAS website[9] and section 2.
3. Third, *sustainability transition support* is needed for stakeholders including decision-makers and farmers. Identifying effective arrangements will require co-developing and studying behavioural change at farm, institutional, and policy level to generate evidence. Key topics include (i) farmers' response to new technologies or policies, (ii) lessons from (un)successful institutional arrangements, and (iii) information systems to accelerate the transitions.

Altogether, sustainable irrigation needs to move towards a global synthesis that sketches the solution space for sustainable irrigation across major food bowls and marginal environments. Our research

[9] https://systems-agronomy.github.io/lcas/module_documentation/10_irrigation.html.

agenda can help to identify positive deviants, understand root problems in unsustainability hotspots, and generate policy momentum for designing and implementing solutions. With several decades of irrigation expansion, Asia is an obvious place to start. But more nascent reports of small-scale irrigation spreading in Sub-Saharan Africa call for cross-learning, testing solutions in new contexts, and applying caution where developments bear marks of familiar sustainability issues (Izzi *et al* 2021). Free electricity is arguably the largest concern. With the current electricity grid in Sub-Saharan Africa it might be wishful thinking but holds large potential to catalyse agriculture. Falling prices of solar panels provide a potentially viable option to mechanise irrigation where the power grid cannot reach. However, off-grid solar pumps are costly and can accelerate groundwater depletion (Balasubramanya *et al* 2024).

5. Conclusions

Sustainable irrigation is a crucial ingredient for many sustainable development challenges. But sustainable irrigation, its configurations, and economics remain a major bottleneck for capturing the value of water. Especially small pump irrigation has surged, but we know relatively little about its extent, economics, and use patterns. With our proposed research agenda, we hope to stimulate further research and policy collaborations on this topic to move towards a global synthesis that empowers policy makers and water managers to help steward water in agriculture and help build inclusive and sustainable food systems.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare no competing interests.

Ethics statement

This research did not include human subjects, human data or tissue, or animals.

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