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Centers for optimizing water management in agroecosystems & global food security

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Global food security (GFS) is challenged by increasing food demand due to population growth and climate change. International trade and globalization have underpinned GFS until the most recent public health, geopolitical and economic crises, when virtually overnight, the focus of governments has shifted towards domestically and locally produced foods. However, the agri-food sector has limited flexibility, and relatively long periods are needed for fundamental/sustainable changes. One of the crucial factors enabling GFS is the efficient water management, but the required knowledge and capabilities are often lacking regionally/locally. We propose the Centers for Optimizing Water Management in Agroecosystems as a long-term solution. The Centers would be the specialized hubs for promotion of research, innovation and technology transfer, raising the knowledge of stakeholders (farmers, extension and government officials, scholars, students, policymakers and other professionals) and their capacities in water management. These Centers would operate as research/education/technology demonstration entities tailored to the specifics of a particular country/region, aiming to address the most important and pertinent goals and outcomes with a high-spatial-resolution outreach. Finally, the Centers will improve farmers' livelihoods, contribute to sustainable and efficient use of agro-environmental resources, and increase productivity and food quality, ultimately supporting GFS.

KEYWORDS

food security, food safety, sustainable water management, demonstration center, climate change, global population

The background: an old problem in a new context

The bioeconomy (based primarily on biogenic rather than fossil resources) has become a contemporary and global imperative in the creation and implementation of (inter) national economic strategies and policies. A driving force for the current paradigm is that the bioeconomy can provide sustainable and long-term solutions for some of the most-pressing challenges for humans, notably economic growth and increasing demand for food (Ahmed et al., 2022), water and raw materials (and their recycling to ensure circular bioeconomy), without compromising the managed and native environments (e.g., von Braun, 2018). Global agri-food sector provides more than a billion jobs and contributes 3% to the global GDP, but 20 to >50% of national GDP in developing countries (FAO, 2020). The protection of agri-food systems and environment is the major pillar of the bioeconomy policy agenda (Galanakis et al., 2022; von Braun, 2018), given its important contribution to sustainable development

(Ansari et al., 2023) through the creation of new businesses/jobs, opportunities and innovations (e.g., *e*farm-to-market-to-table food systems).

Global food security is fundamental to human development (Chen et al., 2022), with 12 out of 17 Sustainable Development Goals (SDGs) having direct relationships with agri-food systems (Bartram et al., 2018; FAO, 2022). Contemporary agroecosystems are resource- and energy-intensive, covering ~43% of the world's ice-free land (excluding deserts); moreover, around 2/3 of freshwater withdrawals are used in irrigated agroecosystems, driving 90 to 95% of global scarcity-weighted water use (Poore and Nemecek, 2018; FAO, 2022). However, global food security is challenged by (i) increasing food demand due to population growth (Sharma et al., 2023; Sakrabani, 2024) and (ii) climate change (Dorward and Giller, 2022; Mbiafeu et al., 2024) (Table 1), both of which have intensified over the last decades and are expected to intensify further by 2050 (Parkinson, 2021; FAO, 2022).

Climate change impacts principal environmental components (soil, water) underpinning food production, gravely threatening rain-fed agroecosystems and grasslands as the predominant (>80%) global *agri-food factories*. Namely, conventional rain-fed agroecosystems on 1.21 billion ha (78% of cropland in the world) contribute 60% of the global food supply, whereas the rest of 349 Mha (22%) of cropland are irrigated agroecosystems providing 40% of the global food supply (Ondrasek et al., 2023). Furthermore, as exemplified by the impact of global warming, with ~1°C rise over the last 50-year period, the freshwater supply in many regions has been impacted by the increased severity of precipitation extremes (floods and droughts, causing frequent and pronounced water stresses) and increasing evapotranspiration rates (e.g., by ~10% between 2003 and 2019) (UNESCO, 2022).

The global population has more than tripled from 1950 (2.5 billion) to the present (8+ billion), and projections suggest a global population of almost 10 billion by 2050 as a medium scenario. To meet the increasing needs for food, the production of the most consumed foodstuff by 2050 will need to increase by up to 110% of current levels (Sharma et al., 2023). However, the total number of livestock has more than tripled, from 7.3 billion units in 1970 to 24.2 billion units in 2011 (UNESCO, 2022), and global irrigated areas increased by more than 4-fold, from ~100 Mha in 1950s to ~470 Mha in 2000s (Thenkabail et al., 2009). If we continue with current management practices, water demand will exceed available water supply by 40% by 2030 (FAO, 2022); thus, it is highly unlikely we can continue with such intensive exploitation of water resources, especially given the current global climate change.

Until recently, globalization was the main driving force (via international trade) in ensuring the increased global food (commodities) demands were met (Muscat et al., 2020). However, the most recent health and geopolitical crises, such as the COVID-19 pandemic (Abu-Bakar et al., 2021), Russian invasion of Ukraine (Hellegers, 2022; Shumilova et al., 2023), and escalated Middle East conflicts (Altemur et al., 2024) have shown how fragile the globalism is and how colossal the impacts its fracturing can have on food safety and security (Abu-Bakar et al., 2021; Liera et al., 2023), global financial markets (Altemur et al., 2024), energy, raw materials, and the total environment (Hellegers, 2022; Shumilova et al., 2023). Self-sufficiency and domestically/locally produced foods have rapidly become the high priority for governments.

The interrupted or impeded commodity export (or uncertainty in supply) due to lockdowns and war-caused shortages impacted agri-food markets severely and increased prices (or made them volatile at least) (Dorward and Giller, 2022). Further price increases are expected due to extreme weather events such as floods, droughts and heat waves in Pakistan, Australia, and African and other countries. The recent food and energy crises have prompted governments worldwide to implement a variety of short-term (*ad hoc*) interventions (Gars et al., 2022; Bergquist et al., 2023). For example, a restriction on agri-food being used as a raw material for bio-energy, temporarily reducing livestock numbers and redirecting animal feed, switching from meat/dairy- to plant-based diet, freezing the prices for basic foodstuffs, and utilization of tax policy instruments (Gars et al., 2022; Sgaravatti et al., 2022). However, agri-food sector is scarcely flexible (Table 1), and relatively long periods are needed for fundamental and sustainable changes to permeate through.

Proposed solution − centers for optimizing water management in agroecosystems

Crop yield quantity and quality are closely related to crop water consumption (Valmassoi and Keller, 2022), whereby increases in water

TABLE 1 SWOT analysis of global food security & proposed solutions – the centers for optimizing water management in agroecosystems.

| Strengths	Weakness	Opportunities	Threats
Optimized water (land, nutrients) use efficiency & management	Initial costs & funding (long-term self-sustainability)	Sustainable water & land management	Rapidly growing global population
Orientation to local resources & food supply	Dependence on technical expertise & technology	Research & innovations	Supply chain disruptions
Minimized food waste	Limited reach & visibility in rural areas	Climate change mitigation & resilience	Environmental pollution & Water overuse
Multidisciplinarity and data-driven decision making	Data management & analysis	Public-private partnerships	Climate change
Collaboration & networking with key stakeholders (farmers, innovators, government)	Resistance to change	Knowledge transfer & implementation	Conflicts & crises (geopolitical, economic, health, armed conflicts)
Contribution to SDGs	Policy & governance constraints	Carbon credits	Inflexibility & inertia of agri-food sector
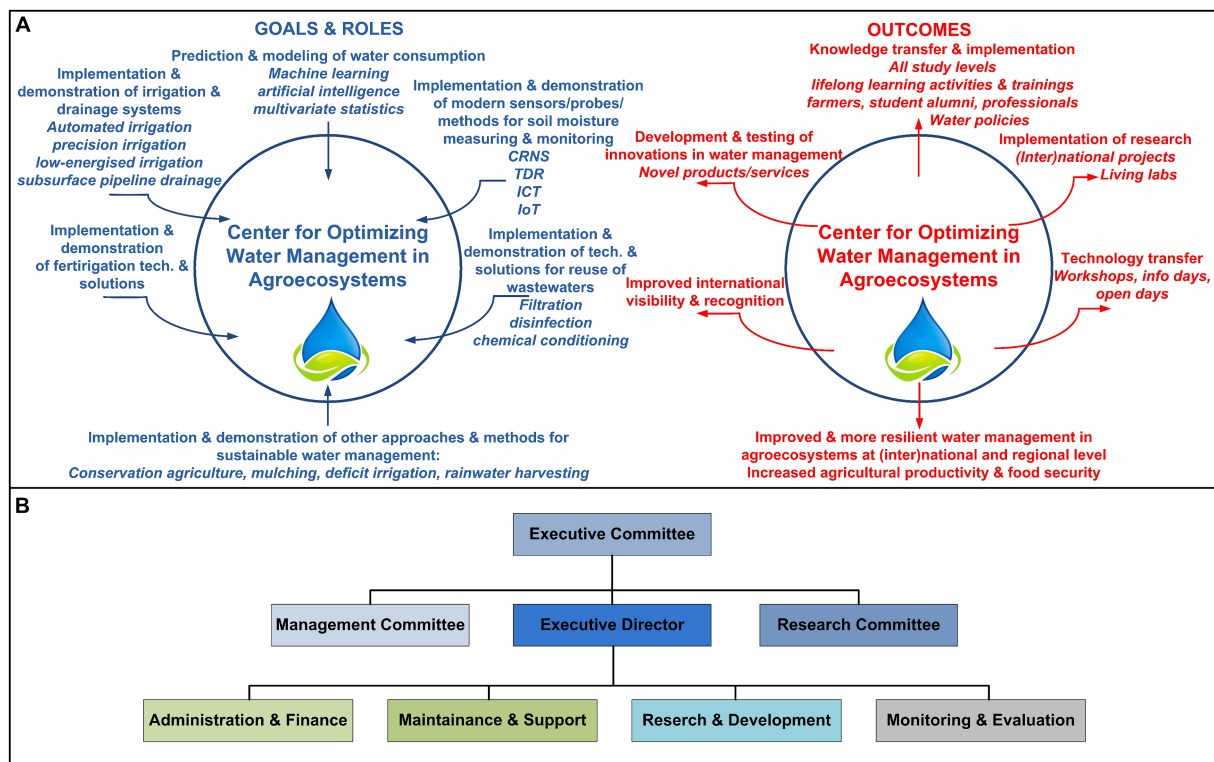
FIGURE 1
The most important goals, roles, and expected outcomes **(A)**, with a proposed organization structure of the centres for optimizing water management in Agroecosystems **(B)**.

consumption (to a certain extent) are related positively to increases in yield and vice versa (Ondrasek et al., 2014). We argue that significant help in improving water management and promoting and intensifying adoption of sustainable agriculture to underpin global food safety and security can be provided by the **Centers for Optimizing Water Management in Agroecosystems** (Figure 1; Table 1). These **Centers** would be the specialized hubs for promotion of research, innovation and technology transfer, raising the knowledge of the stakeholders (farmers, extension and government officials, scholars, students, policy-makers and other professionals) and their capacities in water management (Figure 1). Specifically, each **Center** would operate as an research/education/technology demonstration entity tailored to the specifics of a particular country or region, aiming to address the most important and pertinent goals and outcomes.

Leveraging Information & Communication Technology (ICT) to foster interactions among particular **Center** subdomains (Figure 1) is crucial to accomplishing long-term goals and outcomes. For instance, simulation modeling by using machine learning and artificial intelligence (AI) can allow forecasting of crop water requirements in a particular area and the likelihood of droughts and floods (e.g., Gorlapalli et al., 2022; Narita et al., 2023). The AI algorithms can be used to optimize the performance of water treatment facilities and irrigation systems by analyzing real-time data on water quality, flow rates, soil moisture, precipitation, evapotranspiration, etc. Other (agro)environmental abiotic parameters that vary spatially, such as land constrains, water scarcity/quality, biodiversity, conservation/organic farming practices (Ondrasek et al., 2019; Romić et al., 2020), etc., can be some of input model variables.

There are many soil-based approaches to improving water management and increasing water-use efficiency, such as implementation of conservation practices (terracing, rainwater harvesting, crop residues incorporation, reduced tillage), irrigation technique (deficit irrigation, partial root zone drying), moisture monitoring (advanced sensors coupled with Internet of things – IoT) (Ondrasek et al., 2014; Jones et al., 2023), and their applicability and effectiveness in specific agroecosystems would vary in different countries and regions. For instance, IoT coupled with large-scale and real-time data analytics are currently receiving considerable attention (Reljić et al., 2023; Dong et al., 2024) as possible solutions to the issue of global food security. As of 2015, there were ~30 million IoT devices deployed in agroecosystems (e.g., for water and soil monitoring programs), a figure that more than doubled to >75 million by 2020 (Sharma et al., 2023).

It is expected that the implementation of IoT, data analytics and AI (Figure 1) will ensure a strong support for smart agriculture, leading to increased operational and water-use efficiency and agri-food productivity. Advanced wireless sensors/networks are used in numerous applications related to smart/precision agriculture (Reljić et al., 2023; Dong et al., 2024), food production, and water management (Rani et al., 2022; Jiang et al., 2023). The data and capacity sharing may empower the testing of extremely complex water scenarios on big spatiotemporal scales; such centralized comprehensive assessments of water management in agri-food sector with a high-spatial resolution outreach is sorely lacking. Moreover, the integration of IoT, data analytics and AI technologies is expected to complement the success of multi-scale data integration

methods in smart/precision agriculture, facilitating increased operational efficiency and productivity while enhancing water management across diverse (agro)ecosystems. For example, multi-scale data fusion, incorporating (i) Cosmic Ray Neutron Sensors (CRNS) for *in situ* soil moisture detection, (ii) land surface models (e.g., ERA5-Land, GLDAS-Noah, GLEAM) and (iii) satellite data (e.g., Sentinel-1 SSM, SCAT/Sentinel-1 SWI, SMAP/Sentinel-1 L2), has been successful in assessing soil moisture across various temporal scales within national German ecosystems (grassland, cropland, forest), with promising global applicability (Schmidt et al., 2024).

One of the main obstacles to the long-term self-sustainability of the **Centers** could be external funding. To manage this obstacle, the transition from research and innovation to practical applications must be in the core of the **Centers** mission together with multidisciplinary collaboration to ensure the self-sustainability and national/international visibility and recognition of the **Centers** (Figure 1; Table 1). One of the successful stories regarding regional-to-international centers is CGIAR (Consultative Group on International Agricultural Research) that has spearheaded agricultural R&D for half a century through its 15 research centers/institutes (e.g., International Water Management Institute – IWMI, Africa Rice Center – ARC, International Center for Agricultural Research in the Dry Areas – ICARDA, etc.), numerous partner organizations, and programs aimed at creating more resilient agroecosystems (Meinke et al., 2023); such activities align to goals, activities and outcomes of the proposed **Centers** (Figure 1). High-income nations have recognized the importance of R&D (Howard et al., 2021), and in their long-term policies significant funds have been allocated to it; e.g. in the United States, National Science Foundation supports research and education currently with an $8.8 billion annual budget, and the EU €95+ billion were allocated for research and innovation in just one program (Horizon Europe 2021–2027).

Acknowledging public-private partnerships (PPPs), as well as the self-interest and investment of countries, can significantly contribute to overcoming funding hurdles and enhance the sustainability, effectiveness, and impact of the proposed **Centers** (Table 1). PPPs are recognized as potential solutions for governments, aiming to maximize value for money and finance the necessary investments for infrastructure provision and public service management, particularly in the water sector (Lima et al., 2021). Moreover, there has been a notable increase in studding of the PPP phenomenon in the water sectors of Asia, Europe, and Africa over the past decade (Lima et al., 2021). Recent findings underscore a significant correlation within the Water-Energy-Food (WEF) nexus framework, indicating that countries with superior WEF governance tend to excel in enhancing WEF accessibility, emphasizing the crucial role of governance within the WEF nexus security framework (He et al., 2024). Evidence suggests that countries' self-interests and investments in the **Centers** could an enable the development of local capacity in research, innovation, and management (Cho et al., 2023), allowing them to address specific national priorities (e.g., establishment of the Nitrate Directive) and implement more effective solutions (e.g., reshaping of nitrate-vulnerable zones) (Ondrasek et al., 2021). Additionally, investing in regional centers has been shown to facilitate trans-regional/national collaboration, knowledge sharing (Cho et al., 2023; Torre et al., 2023), pooling of resources, and protection of water resources from pollution/overuse (Ondrasek et al., 2021; Cho et al.,

2023). Studies also indicate that countries investing in the **Centers** demonstrate their commitment to SDGs related to water security, climate resilience and environmental sustainability (e.g., Carvalho and Spataru, 2023; Cho et al., 2023) (Table 1). This commitment can enhance standing of the **Centers** in the global community and attract additional support and partnerships from international donors, investors and institutions.

The resistance to change and poor adoption of new technologies/practices, high implementation costs, cultural resistance as well as limited outreach to farmers and other stakeholders, especially in developing countries and remote areas, are some of the potential barriers. Next, a wide variety of sensors, with different interfaces and incompatible protocols, poses a challenge in terms of software/hardware footprint and hinders the future growth of IoT systems; moreover, such systems rely on the availability of fast wireless connections that are often deficient or even non-existent in remote rural agricultural areas. Therefore, the efficiency of data providing (e.g., encoding) needs to be improved to ensure that the system can function effectively in real time (Sharma et al., 2023).

To overcome some of other barriers (i) innovative and demonstrated solutions need to be reproducible and scalable (e.g., from small to large farms) and (ii) governments should encourage widespread adoption of demonstrated practices through infrastructural projects in rural areas. Some other top-to-bottom strategies and approaches that can be implemented to overcome the challenges associated with the **Centers** targets include:

- capacity building, e.g., specific online or onsite programs/workshops for knowledge transfer among farmers and other stakeholders (Figure 1);
- investments in cloud computing through directly transferring data to reduce the development and management costs (Mytton, 2021; Ramesh et al., 2023), and even contribute to carbon neutrality (Cao and Bian, 2021; Parkinson, 2021) (Table 1);
- standardization, development and implementation of industry-wide standards for advanced ICT solutions (e.g., IoT systems; Mytton, 2021) can help ensure interoperability of protocols and interfaces;
- policy and regulation play a crucial role in promoting the adoption and implementation of advanced systemic solutions (Bartram et al., 2018) in agriculture; therefore, governments must ensure that data privacy and security are guaranteed.

Finally, the principal strengths and opportunities that distinguish proposed **Centers** from existing structures (e.g., IWMI, ARC, ICARDA) include (Table 1; Figure 1):

- focus on optimized water management, whereas existing structures may have broader mandates that encompass various aspects of agriculture, livestock production, food security, and rural development,
- multidisciplinary approach, integrating expertise from diverse areas (agronomy, hydrology, ecology, pedology, statistics, ICT, engineering, etc.) to address complex water challenges comprehensively. In contrast, some existing structures may focus on specific areas like crop improvement (e.g., rice or wheat), livestock or agricultural policy,

- technology & innovation in water management is strongly emphasized, which might not be the case in some existing structures, and.
- close and proactive relationship with water policies and governance. This presents an opportunity for the **Centers** to actively engage in policy advocacy and institutional capacity building by disseminating knowledge through national/regional pilot irrigation projects, living labs, and other initiatives, aiming to reshape water policies effectively.

Conclusion

Recent health and geopolitical crises have shown the fragility of globalism and the importance of prioritizing self-sufficiency and domestically produced food over international trade. However, relatively long timeframes are required for fundamental and sustainable changes in the agri-food sector. As food production is closely linked to water consumption, more efficient water management is crucial for food safety and security. A possible, long-term solution to promote sustainable agriculture and improve water management is to establish the **Centers for Optimizing Water Management in Agroecosystems**. These country and/or regional **Centers** would promote research, innovation and technology transfer among all key stakeholders in water management of agroecosystems, using contemporary approaches (e.g., big-data analytics coupled with machine learning and AI) and techniques (e.g., implementation of IoT, precision and smart irrigation).

Implementation should ensure that **Centers** are accessible to all stakeholders, especially smallholder farmers who may have limited resources and technical expertise. It is important to tailor the services of the **Centers** to the specific needs and challenges of each region or country, considering local conditions, cultures and traditions. Collaboration with local governments, research institutions and non-government organizations can help ensure the relevance and effectiveness of the **Centers**. Funding is a crucial aspect of the **Centers** sustainability; thus, building public-private partnerships and involving international organizations can help secure the necessary resources for their long-term operations. In addition, alternative funding models such as crowdfunding, PPPs or impact investing could be explored to support the **Centers** mission and encourage community engagement.

The proposed **Centers** are distinguished from existing structures by their specialized focus on optimized water management, interdisciplinary approach, emphasis on technology and innovation, and proactive engagement in water policies and governance. Finally, the proposed **Centers** offer a promising solution to improving food security and promoting sustainability in the agri-food sector. By providing guidance and tools for effective water management, the **Centers** can help mitigate the impacts of climate change and water scarcity in food production while contributing to broader environmental and social goals.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

GO: Conceptualization, Writing – original draft, Writing – review & editing. ZR: Data curation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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