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The Future of Water for Food

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Globally, water is a bottleneck to food security and, as such, a new approach for water for food is needed. Food insecurity is knocking at every nation's door, including those of the most developed. Moreover, the disruptions in food supply chains that result from continued reliance on a business-as-usual approach of traditional, non-sustainable food and agricultural systems make food insecurity even more vividly present. This article explores the current relationship between food production and water resources. It attempts to better understand how we might reduce the inter-dependencies between food and fresh water by exploring new and alternative sources of water, including improving the efficiencies of green and recycled water.

Keywords: water-energy-food (WEF) resources, synergy driven models, green-water management, green-water accounting, wastewater reuse, water use efficiency and precision irrigation, water productivity

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INTRODUCTION

The interconnectedness of Water, Energy, Food resources is extreme, especially as these exist in the dryland regions of the world, such as the Middle East and North Africa (MENA) region. Water in particular is key for the entire food supply chain, including production and processing (Uhlenbrook et al., 2022). This paper will focus on the production side of the food system. These resources face the threat of future supply gaps, making better understanding their complexities and reducing inter-dependencies critical to ensuring community resilience. This article highlights the challenges posed by the already existing shortfalls in water, food, and energy resources and their interconnected subsystems. These challenges will only increase over the next 20 years. Lautze (2020) discussed actionable steps that the WEF nexus community must take to move the needle forward. He recommended their actions: demonstration of impact and on the ground utility, keeping the nexus message and actions simple, and multidisciplinary engagement of all sectors of the nexus.

Managing the complex and interlinked system of systems that are WEF resources must include addressing the challenges posed by issues of equity, variability in distribution, and unsustainable consumption. Much of the scientific literature fails to highlight these important and alarming issues. The non-stationary and extreme nature of the natural processes governing WEF subsystems is worrisome: we lack the tools to address the challenges they present. The current business approach for how our food is produced and managed needs revision.

Communities currently manage water resources based on the allocation of existing resources; but with climate and land-use changes, the total available water resources at the needed time and location are also changing and becoming more severe. A revised business approach is essential and must be based on the dynamic interactions and synergies of the interlinked primary resources of water, energy, and food. An example of managing water resources is the current conflict in the Nile River Basin: the GERD dam being built by Ethiopia has implications for the water supply of downstream communities. The approach fails because it changes the water allocation to those downstream communities. Success demands that it be transformed into a synergy-driven approach that realistically valorizes the resources rather than solely allocates them. Similar observations on synergy were reported by Sadoff et al. (2020), looking into achieving Sustainable Development Goal 6 on water security.

This article explores four areas of potential new water sources that can produce a transformative approach to the future of water for food. These four areas are: green-water management and accounting, wastewater reuse, water use efficiency and precision irrigation, and approaches to increase water productivity (**Figure 1**).

ALTERNATIVE WATER

Proper management of WEF resources enables resilient, sustainable communities. Such management must not ignore the role of soils, an important focal point for water and food security that receives very little attention in many current projections, especially for water. A simple example: all our soil maps, whether the FAO Digital Soil Map of the World (DSMW), the US SSURGO Database, or others, are based on rigid, non-dynamic soil maps that rely on soil texture. Today we know that soil *texture* does not reflect soil *functionality*. Dynamic soil mapping is critical to understanding the functionality of a soil system. Such mapping would evolve with time in response to external changes such as management, climate, and evolutions of soil structure. This is important because most food production depends on non-irrigated, rain-fed agriculture. Dynamic soil mapping offers an extremely important and better understanding of the soil through dynamic characterization of the soil medium (Braudeau and Mohtar, 2009; Assi et al., 2014; Braudeau et al., 2016).

A new relationship for water for food must be considered: one in which alternative water resources and new management strategies are explored alongside discussions about water efficiency and water productivity. Green water management, wastewater reuse, and smart irrigation technologies (**Figure 1**) are all pieces of the puzzle that must be stitched together to develop a new plan for understanding the interdependencies between water and food.

Consider that 60% of global food production comes from rain-fed (green water) agriculture, while 70% of the global water withdrawals are used for irrigation. This reflects the importance of green water: cereal production relies mainly on green water, and seed production would decrease by only 20% without blue water. Irrigation (only about 5% in Africa) is globally on 20% of the arable land but produces 40% of the global food. Sustainable irrigation is key to increasing the resilience of food systems. Analysis of global consumption of green and blue water highlights that green (rain-fed) water is much more significant than blue (irrigated) water in many dryland regions. The difference between the two is that blue water is surface water found in lakes, rivers, and aquifers (it is the ground water pumped for irrigated agriculture), while soils are the storage reservoir for the green water that falls as rain or is added through irrigation from blue-water reservoirs (Sulser et al., 2009; Cosgrove and Rijsberman, 2010; Siebert and Döll, 2010). For a set of studies conducted in northern Africa, most of the water resources were estimated to be green water which, though ignored for many years, is a larger pool as compared to blue water resources. Virtual (tradable) green water must also be considered: the most tradable virtual water is green water and comprises most of the flow observed on the global map. The economic importance of green water is very significant and must not be ignored by the science community (Liu et al., 2009; Aldaya et al., 2010).

However, green water lacks a unified definition and therein lies the challenge. Simply put, green water is the water that remains in the soil after rainfall; however, this definition begs the question of whether it is storage and *total transpiration* (Gerten et al., 2004), or storage and *evapotranspiration* (Falkenmark and Rockstrom, 2006). Until we have convergence on a single definition of green water, challenges to accountability will be posed. We will return to this matter below in discussing the pedostructure concept.

Most soil maps are static. A dynamic representation of the soil medium includes mapping of the medium over three axes. The *pedology plane* is the evolution and natural morphology of the soil material; the *vertical plane* is what hydrologists attempt to quantify using parameters without physical meaning or physical connection in the pedology plane. Therein lies the disconnect. Most of us are familiar with the concept of representative elementary volume, used in many computational engineering applications. In soil science, this concept fails to determine which "volume" is referred to in soil hydrology and soil processes (Braudeau et al., 2004, 2016; Braudeau and Mohtar, 2009).

The common denominator for soil is mass that it does not change over time. The volume shrinks and swells, making volume not useful as an independent variable and basis for soil dynamics modeling such as the representative elementary volume (REV). Many of us use hydraulic conductivity parameters that are not grounded in soil pedology. Over the last many years, we have worked to bridge the gaps between the system's *functionalities,* striving to ground them in soil mapping. To this end, we introduced the *pedostructure concept* of identifying *soil hydro-structural properties* by their *behaviors.* Using the pedostructure concept, we re-derived all the constitutive equations related to soil and water. An example of such a re-derived continuity equation is water content as a kilogram of water per kilogram of soil (Braudeau and Mohtar, 2014; Braudeau et al., 2014a,b).

Pedostructure uniquely characterizes a given soil based on that soil's unique properties and using 15 parameters, each of which is measured in the lab and uniquely verified in the field. This characterization provides the shrinkage curve, or *specific volume* which is the inverse of bulk density on the y-axis (Braudeau et al., 2004). On the X axis, we see the water content (Braudeau et al., 2014a,b). Beginning at that point at which the medium is fully saturated, one continuously measures the volume change and the change in moisture content to construct what we named the *shrinkage curve.* The shrinkage curve has most of the properties needed to characterize a medium called gravitational water, which is unique from inter-pedal water. After the gravitational water drains, soil shrinkage is significant. This is the point

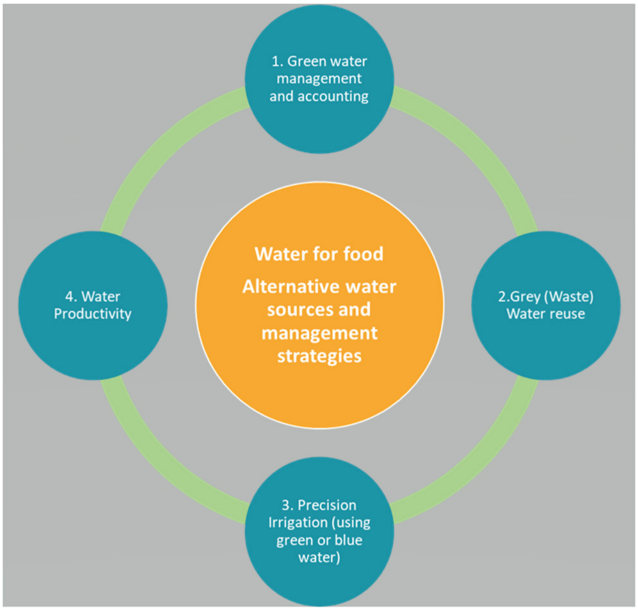

FIGURE 1 | Alternative water management approaches to support food security.

commonly known as the field capacity: the gravitational water or the moisture retained by the water matrix. Field capacity is a very useful term however, it is also a very conceptual term and until now, not physically quantified.

Using the pedostructure concept, we derive the second and third derivatives of the shrinkage curve, which allow us to precisely determine Field Capacity. Following the drying cycle, soil status reaches the permanent wilting point: that point at which all the water accessible for plant extraction is depleted and beyond which point, the plant ceases to grow. We can precisely identify and quantify this point, which has great importance for **precision irrigation** (Assi et al., 2018; Mother and Assi, 2018).

Imagine a future when, using this knowledge, we can track the soil medium from saturation to complete desiccation. At Field Capacity, the gravitational water is lost. Until now, without excess water as part of the drainage, we quantified this water and traced the shrinkage up to the permanent wilting point, that point which, from an agronomic perspective, we do not want to reach. Rather, we stop at a place above the permanent wilting point and at which the plant is not stressed. The future of irrigation lies in the way in which the most advanced knowledge of soil physics allows precision irrigation at the right time and place. Uhlenbrook et al. (2022) argue that this agricultural water use should be embedded in a larger systems approach creating the basis for policy and incentive schemes to optimize the water use for food production.

Enhancing Green Water and Improving Crop Production

"Blue Water" resources are especially limited in arid and semi-arid regions and thus, rainfed agricultural production takes on a vital role in contributing to food security. For centuries, several technologies and soil, water, and crop management practices have been used to improve "Green Water" resources. Rain harvesting technologies and conservation agriculture are known to address water shortage and increase soil fertility and crop yield. Investing in these two critical areas increases the soil water holding capacity and that portion of rainfall available for crop production. The soil's water holding capacity increases as its organic matter content increases. A one percent increase in organic content can improve soil water holding capacity by as much as 1.5% for sandy and 0.6% for silt loams or silt-clay loams (Libohova et al., 2018). Soil degradation is a serious challenge, a key limiting factor that hinders efficacy of rainfall and consequently of crop production. The cascading effects of soil degradation, including loss of soil fertility and organic matter content, lead to declining crop yields and increased human community impoverishment (Barrett and Bevis, 2015).

Since ancient times, rainfall harvesting is a common practice across the globe, especially in arid and semi-arid environments. This practice improves water harvesting and increases the efficacy of rainfall by capturing, diverting, and storing precipitation for crop production and human and animal consumption. Further, it helps minimize soil erosion and protects the environment. Thus, conservation agriculture and rainfall harvesting improve the efficiency of "green water" and enhance its contribution to food security.

Two additional, and very important, elements to consider are **wastewater reuse** and the long-term impact on soil from exposure to different types of water for irrigation. One example is a specific case study conducted in San Angelo, Texas, in which a specific block of land whose groundwater is very salty, was irrigated for 10 years with good quality wastewater. Results showed that, in this case, irrigation with wastewater is far better in terms of crop yield and soil properties than the use of groundwater would have been (Loy et al., 2018). However, this is not the situation in all locations. For example, in Jordan or Lebanon, the outcome could be quite different. While reuse is important, the long-term impact on the ecosystem in which the soil is exposed to reused irrigation water must also be considered. A project conducted in Tunisia focused on a wastewater treatment plan for water, energy, and food (WEF) (Dare et al., 2017). Though very complex due to the social issues regarding the use of wastewater on soil for food and the perception that wastewater is unsafe, the exercise addressed the feasibility at all these dimensions.

To determine the quantity of reused water available for agriculture, one must first calculate the water required for the environment, for ground water recharge, and for industrial and system losses. Agricultural demands must then be mapped: if the treatment plant is too far from the aggregated field, it may be too expensive to pump water to the field. The trade-offs are then calculated: the evaluation of the water-energy-food nexus trade-off as a function of the productive use of water. In the Tunisian case study, we were able to provide 6,200,000 m^3 of water per year that were made available by this plan for irrigation use. However, the trade-off between the abstraction pumping and trucking must also be considered: available water and available energy allow irrigation of 3.6 hectare (IRENA, 2015). The exercise must be globalized to allow real consideration of the potential reuse of wastewater (Mohtar, 2015).

This discussion began around the concept of **water productivity** and the **value of water**. Such value should be inclusive of economic, social, and cultural attributes. Currently, agriculture consumes two-thirds of global freshwater. Such consumption in the future is an unaffordable luxury: to maintain productivity, we must look at alternative water, including blue water as our first choice and alternative water sources. The business approach must be revised. Today, when a farmer is asked about water productivity, the response will be in tons per hectare or tons of produce per hectare of land. This utterly fails to consider the *value* of the water used for that production. It also fails to assign value to energy, air quality, or impact on soil. This must change—we should consider the biomass production and the nutritional value per area. We must look at the existing nexus of complexities in a new, value-based production system that considers nutritional output, water footprint, energy footprint, plant footprint, soil-health implications, air quality, water quality, etc. Though not easy, it must be done. Efficiency is necessary but insufficient where water productivity is concerned. Lebanon, for example, exports potato and other cheap produce without accounting for the loss of virtual water involved in such exports. The new agriculture business approach must properly value water, and in this context, green water cannot be ignored. Green water is a huge resource, one whose use must be maximized given what we know today about soil-water interaction and how much green water and brackish wastewater can be effectively used for agriculture production.

In the context of the Sustainable Development Goals (SDGs), alternative water is critically important. The SDGs address zero hunger and good health. Recycling looks at effective, value-based production, at clean water, sanitation, no poverty, sustainable cities, and communities. Communities are highly relevant for wastewater reuse: the trade-off between pumping and abstraction relates to whether we can build our wastewater treatment facilities close enough to production units to allow full utilization of that reuse.

CONCLUSION

We have green water and blue water: the first requires the development of a functional definition to replace existing definitions. A good definition that is quantifiable and can be generalized is presented by Assi et al. (2018). Convergence is necessary: without that definition, green water cannot be quantified. We must develop a quantitative method to account for green water. Also, we must develop effective methodologies for both field and watershed scales. Non-traditional water, including gray water, must be considered for irrigation in arid and semi-arid regions. Wastewater safety must be considered in terms of the long-term impact and scope of reuse on health and productivity. Finally, we need to understandbetter the interlinkages and trade-offs between society, environment, and water allocation strategies. The current business approach has failed—and will continue to fail. We must look at alternatives approaches that address social, economic, environmental, and cultural attributes.

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RM and AF contributed equally in all aspects of the work and manuscript preparation. Both authors contributed to the article and approved the submitted version.

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