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FEATURE

Agriculture in the North Western Sahara Aquifer System: A miracle in the making?

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The Sahara Desert, a vast, seemingly empty land mass covered with sand or sand dunes with sparse, if any, scrub vegetation, covers an area of 9.4 × 10^6 km^2 (3.63 × 10^6 mi^2) (Abotalib et al. 2016). Sahara is a feminine name based on an Arabic word *sahrā* or "desert." It extends from Atlantic Ocean in the west to the Red Sea Hills in the east, and from Mediterranean Sea in the north to the Sahel Zone in the south. Because of the arid climate, average annual precipitation of less than 5 mm (0.2 in) (New et al. 2000), and harsh environments, agriculture traditionally has been confined to specific areas called oases (small patches of vegetation fed by a spring and surrounded by desert).

Thus, the African continent, where the Sahara Desert is located, is characterized by the familiar bleak statistics, such as 300 million people without access to safe drinking water and only 5% of arable land being irrigated (Tornhill 2012). Furthermore, prevalence of undernourishment in Africa (the percentage of the total population prone to lack of access to safe and healthy food) has been on the rise and was 44.4% in 2014, 49.7% in 2016, 51.3% in 2018, 52.4% in 2019, and 56.0% in 2020. Of this, prevalence of severe undernourishment (percentage of total population) was 16.7% in 2014, 19.2% in 2016, 19.3% in 2018, 31.9% in 2019, 32.2% in 2020, and 34.4% in 2021 (FAO et al. 2022).The problem of food insecurity is presumably aggravated by the current and projected increase in population, especially that of sub-Saharan Africa. The populations of Europe and North America combined (1.18 billion) and that of sub-Saharan Africa (1.2 billion) were similar in 2022. However, the rate of increase in population has been less than 1% in Europe and North America since the 1960s and is reaching the level of zero growth in 2020 and 2021 (UN 2022). In comparison, the annual rate of population growth in sub-Saharan Africa peaked at 3% in 1978 and remained above 2.8% in the 1980s; it is now the region with the fastest growing population, which is projected to double by 2040 (UN 2022).

Similar to the historic concerns about South Asia and China, there are many discouraging questions: Who will feed Africa? Can Africa feed itself? Are there enough natural resources to feed the growing population?" In the final analysis, it is Africa that will feed its population, and it has natural resources to do so (Muang and Andrews 2014). Instead, it is a question of when its policy makers will create environments (pro-nature, pro-farmers, pro-agriculture, and pro-innovations) that translate known science into action (World Bank 2012).

It is precisely in this context that recent agricultural progress in the Sahara is an important indication that Africa has an abundance of water (even under the Sahara), and indeed, can be the future breadbasket of the world. The objective of this article is to describe some recent advances in promoting intensive agriculture in the Sahara Desert based on water conservation and management (drip fertigation) from the shallow aquifer beneath the sand.

WATER RESOURCES BENEATH THE SAHARA DESERT

The Sahara Desert is an arid environment with little, if any, rainfall (New et al. 2000). Further, obtaining credible estimates of rainfall in the region is a major challenge. Thus, other variables (e.g., temperature, air mass movement, vegetation cover, latitude and longitude, etc.) have been used for estimating the effective rainfall amount (Bachir et al. 2016, 2022).

Despite the present arid environment, the Sahara Desert has vast aquifers at shallow depths. These aquifers were created during the Paleo climatic regimes of the North African Sahara characterized by the alternating wet and dry periods over the past several million years (Abotalib et al. 2016). During the Green Sahara period (11,000 to 5,000 years before the present), the Sahara Desert received high amounts of rainfall (Tierney et al. 2017). Early Holocene greening of the Sahara required Mediterranean winter rainfall (Cheddadi et al. 2020). Such wet periods supported diverse vegetation, permanent lakes, and human population. Thus, the aquifers of North Africa were recharged during the wet periods. Consequently, massive underground reserves of water have been found and mapped in several of Africa's desert areas, including those beneath the Sahara Desert (Tornhill 2012).

The Nubian Sandstone Aquifer System, the world's largest fossil water aquifer system, covers over 2.6 × 10^6 km^2 (1.0 × 10^6 mi^2), including parts of Egypt, Libya, Sudan and Chad (Abed El Samie and Sadek 2001; IAEA/UNDP/GEF 2007; Brittain 2015; Abotalib et al. 2016). In addition to the Nubian Sandstone Aquifer System, other large fossil water aquifer systems include the following: (1) North Western Sahara Aquifer System (NWSAS; 1.2 × 10^6 km^2 [0.46 × 10^6 mi^2]) covering Algeria, Tunisia, and Libya; and (2) some smaller aquifers (<900 × 10^3 km^2 [347.4 × 10^3 mi^2]), such as the Iullemedon Aqifer, the Western Sahara Aquifer, and the Taoudeni Aquifer (IGRAC 2021).

AGRICULTURE DEVELOPMENTS IN THE NORTH WESTERN SAHARA AQUIFER SYSTEM

The NWSAS covers an area of 700,000 km^2 in Algeria, 250,000 km^2 in Libya, and 80,000 km^2 in Tunisia (270,000 mi^2,

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96,500 mi², and 30,800 mi², respectively). It is North Africa's largest groundwater reserve. This vast aquifer, currently supporting the life of some 4.8 million people, is located in an arid environment and is thus vulnerable to low natural recharge. Yet, intensive agriculture has developed since 1990s, and the current water use, estimated at 1×10^9 m³ y⁻¹ (3.531×10^{10} ft³ yr⁻¹), is presumably three times the aquifer's natural recharge rate (UN Water 2021). Intensive use may result in adverse impacts on water and soil quality leading to decline in agricultural productivity and increased energy demand through pumping of deep wells. Fragile ecosystems (i.e., wetlands) and people are vulnerable to threat of ecosystem and environmental degradation (UN Water 2021).

INTENSIVE AGRICULTURE AND DEPLETION OF AQUIFERS

Traditional agriculture, developed around some oases, has been used in the Sahara for millennia. One such example is that of the ghouts system practiced in the El Oued region of Algeria primarily for growing dates (*Phoenix dactylifera* L.; figure 1). This nature-friendly and sustainable system is widely practiced with site-specific modifications of species used and management systems, which involve the use of fossil water and recycling of plant nutrients through compost and other biomass.

In contrast, intensive agriculture is now being widely practiced by using the water resources from the aquifers. Some agricultural farms document high productivity of fish or aquaculture (figure 2a), as well as dates grown with a drainage network to remove saline water (figures 2b and 2c). Several crops are also grown with locally made sprinkler pivot systems (figure 3). Land areas of 5 to 10 ha (7.5 to 12.5 ac) are delineated with a sand dikes reinforced with plastic and date palm leaves to protect against blowing wind. Common crops grown with this system include onion (*Allium cepa* L.) and garlic (*Allium sativum* L.; figure 3a); potatoes (*Solanum tuberosum* L.; 30 t ha⁻¹ [13 tn ac⁻¹]; figures 3b and 3c); alfalfa (*Medicago stativa* L.; figure 3d); plantations of olive (*Olea europaea* L.), pomegranates (*Punica granatum* L.), dates, and citrus with drip irrigation (figure 3e); and sunflowers (*Helianthus annuus* L.; figure 3f), along with corn (*Zea mays* L.) and other grain crops with sprinkler pivot systems. The intensive system of agriculture using perennials is essentially a sand culture based on use of compost/manure (in close proximity to the plant), along with chemical fertilizers and irrigation (for crops like date palm, olive, pomegranate, and citrus). Selective use of compost in the root zone improves water retention in the root zone, and it is supplemented by inputs of chemical fertilizers.

Figure 1
(a) Traditional Sahara landscape, (b) the traditional ghout system of farming date palm. The ghout system consists of digging into the sand to plant date palm at the top of the groundwater. The ghout system, built on an oasis located in the Wilaya of El Oued in southeastern Algeria, has been used since the 15th century by the local Sufi communities to grow dates.

(a)

(b)

Figure 2

Intensive farming in sandy soils with a high water table (1 to 2 m below the sand) in the North Western Sahara Aquifer System: (a) aquaculture, (b) date plantation, with surface drains installed to remove brackish water, and (c) a large canal network to drain the brackish water.

Vegetables are also grown under plastic houses (figure 4), including tomatoes (*Solanum lycopersicum* L.; figure 4a) with drip fertigation (figure 4b) and watermelon (*Citrullus lanatus*). Indeed, high quality vegetables are produced using sand culture under the plastic houses (figure 4c) (Monk 2016).

CHALLENGES TO INTENSIVE AGRICULTURE SYSTEMS

The climate of the Sahara has changed in the past and is changing at present because of anthropogenic perturbations. Some estimates indicate that, with increasing atmospheric concentration of greenhouse gases from 1980s to the 2090s, the Sahara may be becoming smaller, moving north and west, and continuing to dry (Liu et al. 2001). On the contrary, Thomas and Nigam (2018) reported that the Sahara Desert has expanded significantly over the 20th century by 11% to 18%, depending on the season, and by 10% when defined by rainfall. In the future, the Sahara region could experience more rainfall than now as a result of climate change.

In addition to current and projected climate change, labor availability and water quantity and quality may be other factors affecting agricultural operations. Most farm operations (using compost, transplanting, and harvesting of vegetables) are performed by manual labor. The fossil water, seemingly available in large amount, may be nonrenewable. Furthermore, the water is brackish and aggravates risks of secondary salinization. Renewability of the NWSAS aquifer system is debatable and considered by some as renewable and by others as nonrenewable. Such controversy can only be resolved through measurement and monitoring of the water resources by careful study of water and salt balance in agroecosystems over a long-term basis.

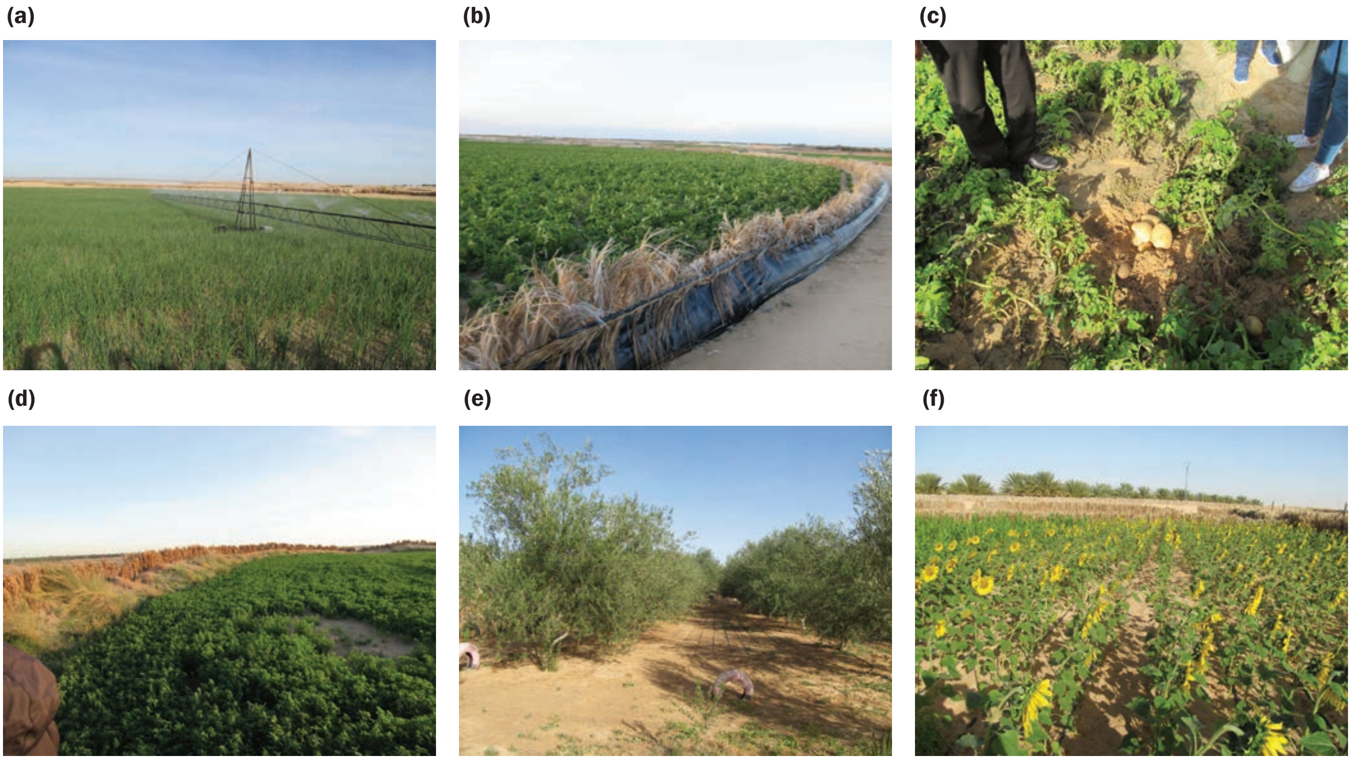
Al-Gamel (2010) assessed renewability of the NWSAS to determine whether it receives a considerable fraction of modern water as recharge or is at risk of being depleted by excessive pumping. Al-Gamel concluded that the NWSAS is not a nonrenewable resource and indicated that NWSAS classification as nonrenewable would be misleading and an obvious inaccuracy of the facts.

On the contrary, however, there are also some critical reports stating the adverse impacts of intensive agriculture on depletion of the aquifer and degradation of fragile ecosystems because the brackish water and limited recharge. Chekirab et al. (2022) developed a hydroeconomic model of the NWSAS using data from 1955 to 2000. They observed that the NWSAS aquifer comprises of multilayer reservoir with vertical exchanges. They assessed the impacts of intensive pumping on the depletion of groundwater and documented the trajectories of piezometric levels. Chekirab and colleagues predicted that some reservoirs may be completely depleted by 2050.

Mohamed and Goncalves (2021) reported that the NWSAS is challenged by an unsustainable groundwater system

Figure 3

(a) Locally made pivot sprinkler irrigation system, (b) 5 to 10 ha farms are surrounded by a dike reinforced by plastic and palm leaves to protect against windblown sand, (c) a potato field planted and harvested by manual labor, (d) alfalfa grown as fodder, (e) an olive plantation, and (f) sunflower grown adjacent to a plot of corn and vegetables.



especially when the knowledge about the recharge system is scanty. Based on a study between 2002 and 2016, Mohamed and Goncalves observed the effective recharge value of 1.76 mm y^{-1} (0.7 in yr^{-1}) and concluded that the anthropogenic factor is the primary controlling factor. They also observed that average annual rainfall suggests a recharge of about 1.8% in transboundary aquifers of the Saharan belt.

UN Water (2021) assessed the water-food-energy ecosystem nexus in the NWSAS and emphasized the need for conservation and sustainable management of water resources in the Sahara. The UNECE (2021) and the Global Water Partnership also emphasized the need for reconciling resource uses in the NWSAS and stated the urgency of taking action across nations and sectors to address the threats to degradation of aquifer systems. Therefore, judicious use of finite resources and long-term measurement and monitoring to assess the ecological impacts of agricultural intensification in Sahara are essential.

MEASUREMENT AND MONITORING OF AQUIFER AND SOIL RESOURCES

Whereas adoption of intensive agricultural systems is recent, the need for measurement and monitoring of aquifer and soil resources under agroecosystems is more urgent now than ever before (Mohamed and Goncalves 2021; Semar et al. 2019, 2021). Not only should the recharge mechanisms be evaluated using isotopes and other modern techniques (Al-Gamel 2010), the potential for green agricultural development in fragile environments must be based on credible data on management-induced changes in soil properties (e.g., salinity and alkalinity). Periodic measurements of soil and water balance, along with evaluation of soil and water salinity, are critical in new agricultural land under harsh, arid climates (Semar et al. 2019). The strategy is to produce more from less with focus on optimum and sustainable production rather than maximum production based on high consumption of natural resources.

STRATEGIC PLAN AND RESEARCHABLE PRIORITIES

Long-term effects of these intensive systems are not known and thus are a researchable priority.

National agricultural research centers in cooperation with regional universities may develop a long-term research-education-extension program on sustainable management of natural resources with the focus on carbon (C, soil and biomass), water, salt budget, gaseous fluxes, and nutritional quality of food produced.

Therefore, assuring environmental sustainability of the new and innovative system necessitates the following plan of action:

1. Periodic assessment of soil health: It is critical to assess dynamics of soil health on a regular basis with reference to the baseline (native ecosystem). Specific attention should be given to soil properties such as chemical (electrical conductivity, pH, nutrient budget), biological (soil organic C [SOC], microbial biomass C, species

Figure 4

Vegetables grown under plastic houses: (a) tomatoes on trellis, (b) a drip fertigation system, and (c) high quality vegetables produced under plastic houses.

(a) (b) (c)

diversity), physical (albedo, temperature, moisture retention, gaseous fluxes especially of nitrous oxide [N_2O] and methane [CH_4]), and ecological properties (salinization, water pollution and eutrophication, change in soil biodiversity including activity and diversity of soil biota, and wind erosion). Managing water and salt balance is the key to long-term sustainability. Salt buildup was observed on the soil surface in several farms visited, and minimizing risks of secondary salinization is a high priority.

2. Terrestrial C sequestration: There is a strong need to develop a database with regards to rate of sequestration of C in soil (both organic and inorganic) and in biomass (above- and belowground) under diverse farming systems with reference to the baseline.
3. Producing more from less: Rather than maximizing the yield, the goal should be sustaining productivity per unit of land, water, fertilizer input, pesticide use, water consumption, and emission of greenhouse gases. The focus is on environmental sustainability rather than on increasing short-term productivity.

Examples of some specific researchable themes are listed below:

1. Establish an optimal range of SOC content in the root zone of sandy soils to reduce leaching of plant nutrients, increase retention and use efficiency of water, adapt to drought and extreme events, and sustain productivity.
2. Determine saving in water and fertilizer inputs to sandy soils by improving SOC stock by 1 t ha^{-1} (0.45 tn ac^{-1}) in the root zone, and identify site-specific systems that produce more from less.
3. Evaluate rate of sequestration of SOC and soil inorganic C (as pedogenic carbonates and leaching of bicarbonates) under different farming systems.
4. Assess rates of decomposition of mulch (date-palm leaves shredded into different fractions), compost, and manure in relation to temperature and moisture regime and mode of application (e.g., surface versus incorporation).
5. Quantify mean residence time of SOC added to the soil under different cropping/farming systems.
6. Measure flux of greenhouse gases from soil under different systems of management.
7. Analyze nutritional quality and safety of the food produced under different management systems.
8. Evaluate the potential and attainable C sink capacity (terrestrial C) of soils of the West Asia/North Africa region in relation to land use and management systems.
9. Determine societal value of C in soil and biomass in relation to management systems.
10. Establish protocol and mechanism of payments to farmers for provisioning of ecosystem services through adoption of climate-resilient agroecosystems.

CONCLUSIONS

Two critical aspects of the fragile aquifer systems are the water and salt balance in the root zone. Because the NWSAS and other aquifer systems have saline water, the risks of secondary salinization along with depletion of the water resources are critical to sustainable use of these finite resources in fragile ecosystems and harsh environments of the Sahara. There is also a strong urgency to address the need for transboundary cooperation to understand the characteristic hydropedological and hydrogeological attributes and prevalent water use patters for intensive agriculture.

Yet, judicious use of natural resources has a vast potential to sustain agricultural productivity with minimal risks of depletion of water and salinization of soil resources. In this context, the strategy is to produce more from less and focus on an optimal sustainable production rather than on maximizing the production over a short period with adverse impacts on soil, water, biodiversity, and other ecosystem services. With a prudent strategy, and developing and implementing policies that are pro-nature, pro-farmer, and pro-agriculture, Africa has the capacity to feed itself and be a breadbasket of the world. The making of the Saharan miracle, however, depends on prudent governance at country level and cooperation among nations for peaceful coexistence.

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