PERSPECTIVE

The case for distributed irrigation as a development priority in sub-Saharan Africa

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Distributed irrigation systems are those in which the water access (via pump or human power), distribution (via furrow, watering can, sprinkler, drip lines, etc.), and use all occur at or near the same location. Distributed systems are typically privately owned and managed by individuals or groups, in contrast to centralized irrigation systems, which tend to be publicly operated and involve large water extractions and distribution over significant distances for use by scores of farmers. Here we draw on a growing body of evidence on smallholder farmers, distributed irrigation systems, and land and water resource availability across sub-Saharan Africa (SSA) to show how investments in distributed smallholder irrigation technologies might be used to (*i*) use the water sources of SSA more productively, (*ii*) improve nutritional outcomes and rural development throughout SSA, and (*iii*) narrow the income disparities that permit widespread hunger to persist despite aggregate economic advancement.

agriculture | food security

Irrigation has been a cornerstone of agriculture for thousands of years and has helped food production expand apace with population growth (1). Today, the 18% of global cropland that receives irrigation water accounts for about 40% of global food production (2). In Asia, where 37% of the cropland is currently irrigated (Fig. 1) (3), governments and international agencies responded to major famines of the 1960–1970s with large-scale investments in irrigation, improved crop varieties, and fertilizer. This development strategy—the Green Revolution—was as much a story of water as it was of modern crop technology. Irrigation enabled year-round crop production, higher yields, growth in rural incomes, and a dramatic reduction in acute and chronic hunger.

In sub-Saharan Africa (SSA), by contrast, only 4% of agricultural land is irrigated. Although an estimated 40 million ha are suitable for irrigation, only 7.3 million ha are actually irrigated, and the vast majority of this irrigated land is concentrated in just four countries: Madagascar, Nigeria, South Africa, and Sudan (3) (Fig. 2). SSA is the only region in the world where per-capita production of staples has declined over the last half-century and where major famines persist, the majority being triggered by drought and erratic weather (4, 5). Although achieving food security in SSA is a multifaceted effort, evidence from across scales—from household to watershed to continent—suggests that more reliable access to water, especially in the form of smallholder irrigation, has great potential to reduce hunger, raise incomes, and improve development prospects in the region.

In recent years, calls for a "uniquely African Green Revolution" have led to institutional alignment within the Comprehensive Africa Agricultural Development Program (CAADP), under which the majority of African governments have agreed to allocate at least 10% of their budgets to agricultural development. Meanwhile, private foundation activities, such as those of the Alliance for a Green Revolution in Africa (AGRA) funded by the Bill and Melinda Gates and the Rockefeller Foundations and the Collaborative Crop Research Program (CCRP) funded by the McKnight Foundation, are allocating a large share of their resources toward crop productivity and nutritional gains for smallholders in some of the poorest areas of SSA. Several activities within the Consultative Group on International Agricultural Research (CGIAR) are also focused on crop productivity improvements for both staple commodity and vegetable crops in SSA. Within these tremendously positive developments, however, widespread action on sustainable water access for smallholders has not yet been catalyzed.

The Case for Distributed Irrigation

Between 1970 and 2004, 26 SSA countries experienced at least 6 droughts, and 14 of them experienced at least 10 droughts, precipitating food crises that resulted in hundreds of thousands of deaths over the period (6, 7). Such famines continue to occur against a backdrop of widespread chronic malnutrition—in the forms of calorie, protein, and micronutrient deficiencies—that afflict roughly one-third of the African population (8, 9). The 2011 famine in the Horn of Africa is a recent reminder of the region's vulnerability to drought and its shortfalls in agricultural development.

Roughly 70% of Africa's extremely poor populations (per capita income of <$1.25/d) live in rural areas and depend primarily on agricultural production for their livelihoods. Although up to 30–40% of their income typically comes from nonfarm activities, even these activities are often closely linked to agriculture (9). Most of these agriculture-dependent communities have little chance of escaping poverty and becoming food secure without a significant change in development strategy, because the very nature of their farming systems keeps them mired in poverty. In most of SSA, smallholder cropping systems are dominated by rainfed cereal (e.g., maize, sorghum, millet) and starchy staple root crops (e.g., yams and sweet potatoes). These crops have limited nutritional benefits, and their low market value makes it difficult for smallholders to

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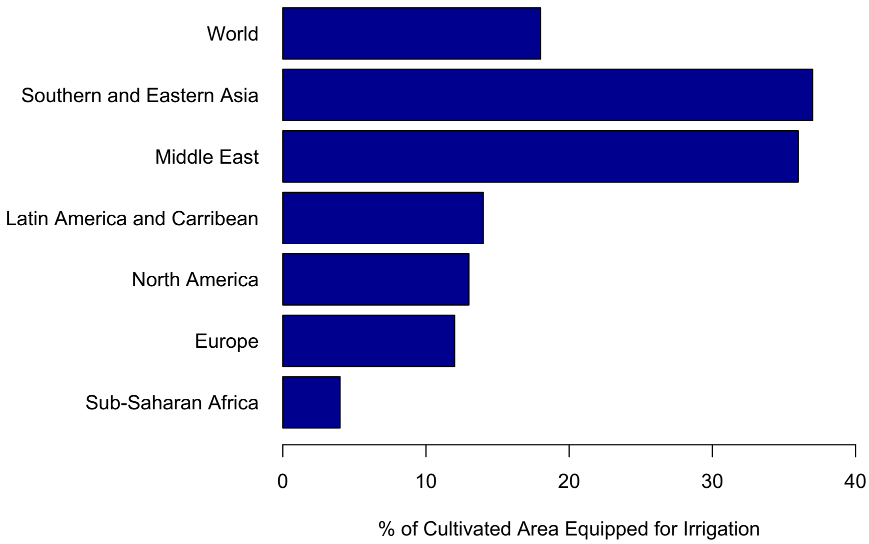

Fig. 1. Irrigation coverage for regions and world. Adapted from (17).

survive economically on their small land base, typically 1–2 ha. Yields for smallholder farmers in SSA remain the lowest in the world, and rapid population growth is reducing the per-capita farmed area, making household food security for smallholder farmers an increasingly challenging goal (2, 10). In the coming decades, the anticipated rise in average temperatures, reductions in soil moisture, and increased rainfall variability are expected to compound the problems of low crop productivity (9, 11–13).

In these rain-fed systems, crop production is limited to a 3- to 6-mo rainy season. The strong seasonality of crop production and weak marketing channels result in local price spikes, peaking malnutrition (most noticeable among children), and overall vulnerability during the dry season. At harvest time, inelastic staples markets and lack of outlet channels create price slumps that inhibit the adoption of productivity-enhancing technologies, thus completing a low-productivity trap.

For these smallholder farmers, irrigation can facilitate several important shifts in household agricultural production and income generation. First, it enables a second cropping season or even year-round production, because farmers are no longer limited by the length of the rainy season. Second, farmers are able to cultivate fruits, vegetables, and other higher-value crops that require more reliable water supplies. Finally, irrigation can mitigate the impacts of climate stress associated with drought and extreme heat.

Although any irrigation system could theoretically facilitate these positive shifts for smallholder farmers in SSA, distributed irrigation—particularly when it is deployed at a large scale—offers a number of important benefits over centralized irrigation infrastructure. Although earlier studies (14) gave large-scale centralized irrigation investments in SSA a reputation of being prohibitively expensive, a more recent and finer-grained analysis finds that distributed irrigation projects covering large areas (i.e., comprised of many small-scale irrigation systems, as opposed to centralized infrastructure) are generally the best in SSA in terms of unit cost and performance (15). The study also found that projects supporting farmer-managed or jointly managed systems (which is typically the case with distributed irrigation) have lower unit costs and better performance outcomes than those managed solely by government agencies. For example, the World Bank–supported Nigerian National Fadama Development Project (1993–1999) was designed to irrigate 50,000 ha with 50,000 tubewells and low-cost motorized pumps; although a large project, each individual system irrigated only 1 ha. Investment in supporting infrastructure (e.g., better access to markets) was included as well. In some Nigerian states, farmers experienced an increase in returns per hectare of 65–500%. Overall, the project garnered an economic

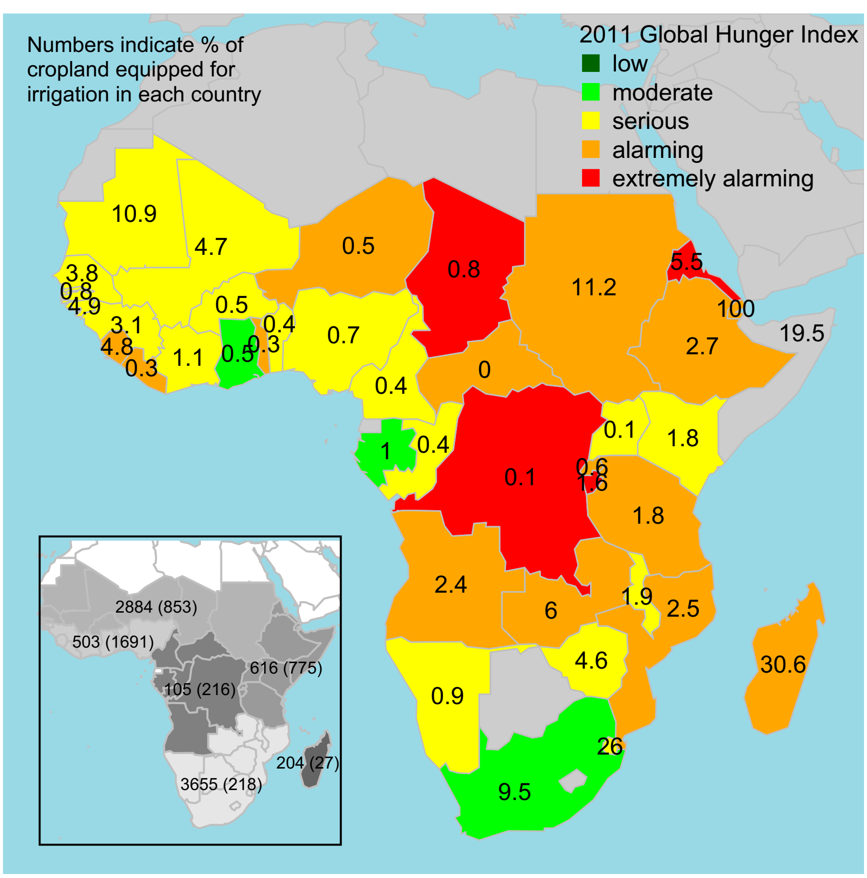

Fig. 2. Color map gives 2011 Global Hunger Index (46); text shows irrigation coverage for SSA nations (3). (Djibouti has very little cropland, all of which is irrigated; it is almost entirely dependent on food imports.) (*Inset*) Total current irrigated area by region, with small-scale profitable expansion potential in parentheses (thousands of hectares). Data from ref. 16.

rate of return of 40%, substantially higher than the appraisal estimate of 24% (14, 15).

Further supporting the economic case for distributed irrigation, a recent modeling study estimated the profitable expansion potential for both large-scale (dam-based) and small-scale (community-level catchments, flood recession farming, tubewells, etc.) irrigation (16). It found that the potential for profitable irrigation expansion through small-scale schemes amounted to 6.6 million ha for SSA, with an estimated internal rate of return (IRR) for such projects averaging 28%. For large dam-based projects, by contrast, the comparable figures were 1.3 million ha of profitable expansion potential and an IRR of 12%. Thus, according to this study, distributed irrigation has five times the expansion potential as large centralized schemes and offers much greater potential profits.

Distributed systems also offer substantial environmental benefits over large centralized systems. They can reduce the soil salinization that has plagued many large-scale surface irrigation schemes, especially those installed without adequate drainage (1). They can also be tailored to local water conditions to maximize the productivity of rainfall, surface water, and groundwater supplies while reducing evaporation losses. This benefit is particularly important in SSA, where the hydro-climatic environment is challenging for crop production and where, especially in the drylands, a large share of precipitation returns to the atmosphere through evapotranspiration. Innovative ways of capturing, channeling, and delivering local rainfall to the root zones of crops are thus critical to raising crop yields and improving harvest reliability. Distributed irrigation schemes can be designed to access and deliver water in ways that maximize water productivity given the local agroecological and hydrological conditions (17).

Further, distributed irrigation can provide more sustainable access to water in much of SSA. Most of the continent south of the Sahara suffers not from physical water scarcity, but from economic water scarcity: in other words, the water is available, but capital to put it to use has not been mobilized (18, 19). In SSA as a whole, annual water withdrawals amount to just 5.5% of total annual internal renewable water resources (IRWR)* (3, 20). Moreover, recent research has found that SSA has groundwater in storage totaling >390,000 km^3—more than 100 times its estimated total renewable water supply (21). Because many of these aquifers are low-yielding, however, small distributed systems of low- or medium-flow boreholes (0.5–5 L/s; suitable for individual and community-scale applications, such as village water taps and vegetable irrigation) may be the most sustainable means of tapping these groundwater reserves (21).

Last, distributed irrigation offers institutional advantages (22). It obviates the need for the massive installation, maintenance, and oversight institutions required by large-scale, centralized irrigation projects. Distributed systems do not require the flooding of valleys—and concomitant forced migration—that large dam-and-reservoir projects do. They are also less prone to corruption and have historically fared better than their privately owned counterparts (23). However, the best case for prioritizing investments in distributed irrigation schemes for smallholders comes from the farmers themselves: although expansion of irrigation in SSA has been meager overall, most that has occurred has been through privately purchased or financed small-scale distributed systems (20). Given information about these technologies and access to financial services, farmers can make private investments in their own farms, independent of large-scale infrastructure and bureaucracy.

Brief Historical Development

Although farmers have used simple manual irrigation technologies for many centuries, the use of distributed irrigation as a pathway out of poverty began in earnest about 25 y ago. Entrepreneurs and non-governmental organizations (NGOs) began developing and manufacturing both low-cost, human-powered treadle pumps and individual-scale, modular drip irrigation kits for poor farmers in South Asia and later in SSA (24). Among the early endeavors was the introduction by iDE (formerly International Development Enterprises) of the foot-operated treadle pump into Bangladesh, where the sale of 1.5 million pumps has been estimated to be netting $150 million annually on $37.5 million in purchase costs and $12 million in donor investments (25).

A decade after the treadle pump's introduction into Bangladesh, the nonprofit KickStart (then Approtec) began marketing the MoneyMaker line of (metal) treadle- and hip- pumps in SSA countries, including Kenya, Mali, Tanzania, and Burkina Faso (along with partnerships in 13 other SSA countries). To date, more than 200,000 pumps have been sold (26). Through follow-up visits to farmers who purchased the pumps, KickStart estimates that their pumps have created $110 million in new wages and profits and have helped move more than 600,000 individuals out of poverty. Baseline surveys have confirmed that most farmers are selling their products locally, providing more evidence for the large (and elastic) local demand for vegetables and fruits that are often high in micronutrients (23, 27).

Over the last decade, the International Crops Research Institute of the Semi-Arid Tropics (ICRISAT-Niger) has helped install thousands of "African Market Gardens" (AMGs)—a holistic irrigation and management package—in nine countries across the Sudano-Sahel region of West Africa (27, 28). These systems ranged in size from 80 to 500 m^2 (for individual farmers) and up to several hectares in communal and cluster configurations. Although little analysis has been done to assess the effectiveness of the more than 2,000 systems installed, one controlled field trial of the AMG in Niger compared it to traditional practices and showed dramatically increased returns on labor, land, and water, as well as improved yields, especially during the long dry season (29). Throughout Niger, farmers who turned to drip irrigation kits and better management techniques to begin producing higher-value vegetable crops often used their new income to invest in labor-saving motorized pumps and to expand their businesses (30).

In recent years, inexpensive motorized pumps (most running on gas or diesel fuel) have entered SSA marketplaces, and their adoption is expanding rapidly in some areas. At about $250 per pump, the capital cost is competitive with higher-end treadle pumps. With the large time- and labor-savings compared with manual pumps, as well as the ability to access groundwater at greater depths, they offer clear advantages. Approximately 30% of small-scale irrigators in Ghana, for instance, now own or lease a motorized pump to irrigate their farm plots. A 3-y study by the International Water Management Institute (IWMI) estimates that small-scale motorized pumps could expand irrigation by about 30 million ha in SSA, generate annual net revenues of $22 billion, and improve food security and incomes for about 185 million people (31). It remains to be seen whether fuel prices and supply reliability constrain the adoption of these pumps.

*Internal renewable water resources (IRWR) is a measure of water generated within a given country (typically on an annual basis). It is equal to runoff + groundwater recharge (from precipitation) + seepage from rivers into aquifers − groundwater drainage into rivers. Total renewable water resources (TRWR) is the sum of IRWR and renewable water generated externally (e.g., runoff originating in a neighboring country).

Synergies of Water Access, Distribution, and Use

All three technology components of distributed irrigation—access, distribution, and use—are necessary for a successful smallholder irrigation system (32). Farmers must be able to access and reliably move water, and they must be able to distribute it to their crops with some degree of efficiency. They must also be able to grow crops that generate profits high enough to render their overall investment profitable (33). Unfortunately, capital constraints often prevent farmers from investing in all three of these complementary components of distributed irrigation, and hence they do not reap maximum returns. Research has shown that, even if two technologies are complementary, farmers will often skimp on a divisible technology (like vegetable seeds or fertilizer) when they have sunk significant capital into a "lumpy" technology (like a pump or an irrigation kit) (34, 35).

Technologies for accessing water pose an especially acute problem. First, even the cheapest pumps may be prohibitively expensive without financing: the KickStart hip pump costs $100, whereas its best-selling treadle pump costs $300 (36). Because these pumps can access water only to a depth of ∼7 m, they are not useful where local water supplies are deeper underground. Further, in some regions of SSA where crop production is strongly gender-divided, and horticulture is seen as a female pursuit, treadle pumps may not be culturally appropriate or simply will not be used (34).

To benefit from irrigation, farmers in these circumstances must turn to other water access technologies, such as gas- or diesel-powered motor pumps, or a share in a community-scale solar-powered water pump. Both of these options save on labor, which can be allocated to other income-generating activities. Girls, who typically haul water for household use, can be sent back to school (32). Although solar systems avoid the fuel constraints of motor pumps, they require a significantly greater initial capital outlay, typically necessitating a community-scale approach.

Unfortunately, microfinance institutions (MFIs) in SSA often do not extend into rural areas (as this raises operating costs), nor do they offer agriculture-related loans (as coordinated risks are high) or loans of a reasonable size for this type of investment (i.e., hundreds of dollars as opposed to tens of dollars). Although MFIs are beginning to pursue interesting combinations of credit and insurance to agricultural borrowers, access to credit has lagged far behind demand for productivity-enhancing technologies like distributed irrigation systems.

Despite these pitfalls, new solutions are emerging for smallholders in SSA. In a welcome development, in 2012, the direct lending site Kiva.org partnered with the One Acre Fund, a smallholder agricultural extension program in Kenya, Uganda, Rwanda, and Burundi, to begin extending agricultural loans to farmer groups (36). In several cases, farmers have organized into groups to overcome physical and economic water access issues. Although the limited literature on farmer groups is mixed (37, 38), success stories tend to be found where distributed systems are used in a cooperative setting, permitting the sharing of knowledge, risk, credit, and marketing (39). For example, the AMG project saw farmers in Niger join together to purchase pumps and also documented greater revenues from communal and cluster models (27).

In one positive pilot study in northern Benin, solar-powered water pumps were used to feed community-scale drip irrigation systems in conjunction with women's farming groups (40). The systems were implemented in an unelectrified rural area with deep groundwater inaccessible with treadle pumps, and the households represented in the participating farming groups were some of the poorest in the region, surviving on well under the extreme poverty line of $1.25 per person per day. An evaluation of the pilot irrigation systems showed a significant positive impact on household food security and income measures after 1 y, as well as some positive spillover effects on community micronutrient consumption. Moreover, the technology itself spurred several positive institutional developments, such as the creation of a new school curriculum module surrounding the technology, educational investments, and the formal registration of women's cooperatives to attain land titles and credit (32, 40).

The Way Forward

The promise of distributed irrigation has led to recent momentum around smallholder irrigation as a development priority. Perhaps most notably, IWMI is currently leading a study funded by the Bill and Melinda Gates Foundation to understand the wider potential of smallholder agricultural water management solutions in SSA and South Asia (41). For this promise to be realized, important questions must be addressed. How can smallholder irrigation be expanded successfully and sustainably in SSA? More specifically, how can the world's poorest smallholder farmers access and benefit from these technologies, without causing the kinds of widespread environmental damage associated with irrigated agriculture in so many other parts of the world, from groundwater depletion to wetlands destruction?

Development of sensible policies to close the gap between the current scale of smallholder irrigation and its full potential rests on progress and research in three critical areas:

(*i*). The development community and SSA governments need a better understanding of present water resources in SSA and how they will be affected by climate change. Recent studies (16, 18, 21, 42) have laid a strong foundation for this work at the national and aquifer scales. Nevertheless, particularly for regions that would be dependent on groundwater for irrigation (21), water resources must be mapped in detail at the local level and monitored to avoid recreating the type of water crisis present in South Asia, where development of privately owned distributed tubewells has contributed to severe aquifer drawdown (43). These assessments should also integrate new understanding of groundwater recharge dynamics (perhaps based on extensive sensor networks) and new modeling of anticipated climate impacts (44). Groundwater surveying at fine spatial scales is prohibitively expensive for individual farmers. Major international donors could make an important contribution by investing in such an undertaking. Two countries ideal for piloting such work would be Niger and Ethiopia; both are drought- and famine-prone and sit atop accessible groundwater resources (21).

(*ii*). The development community needs a better understanding of how SSA smallholders perceive risks to ensure that investments in irrigation systems and diversified horticultural cropping systems are actually risk-reducing from their perspective. The risks might include those arising from technology failure, commodity price swings, storage constraints, pest and pathogen problems, and weather shocks. Such information could help guide agricultural development programs, emerging farm insurance markets, and rural financial institutions. For example, access to "meso-scale" credit (including to farming groups) could be developed and expanded to facilitate complementary input purchases (e.g., pump, irrigation kit, improved seeds, and fertilizers) by smallholder farmers and regional marketing networks. Improving household or community storage capacity for starchy staple crops could help mitigate seasonal price slumps and crop waste and could provide a safety net in years of adverse climate conditions.

(*iii*). Finally, distributed smallholder irrigation systems and large-scale centralized irrigation projects require different institutional arrangements for successful adoption and support (22). No single smallholder irrigation package will be appropriate for all of SSA. Although the lowest-cost technologies (like human-powered pumps or ultra-low-cost drip irrigation kits) may be an accessible entry-level technology for many farmers, these products are not a one-size-fits-all panacea. As a result, farmers need access to financial services—credit and insurance—appropriate for a range of production systems (31, 45). In particular, MFIs providing loans for both individuals and groups to invest in higher-quality, longer-lifetime technologies that bundle access, distribution, and use technologies will be critical for driving productivity in SSA's rural sector.

Given the untapped potential of distributed smallholder irrigation systems, it is time for international donor groups and African governments and institutions to make it an explicit priority investment. Availability and efficient use of water is critical for ongoing fertilizer programs, for year-round crop production, for production of critical micronutrient crops like vegetables and fruits, and for adaptation to projected scenarios of climate change. Investments should start at a smaller scale with thorough project evaluation and then be scaled up in areas where systems benefit smallholder communities in terms of income, education for girls, and health outcomes.

Such prioritization would help catalyze a shift in smallholder production whereby today's localized success stories become tomorrow's continental norm. With targeted investments and policies to expand distributed irrigation, the future for SSA's smallholder farmers could be bright. Without them hunger, poverty, and humanitarian crises will persist throughout much of the continent.

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