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Smallholder Irrigation as a Poverty Alleviation Tool in Sub-Saharan Africa

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Summary. — Promotion of smallholder irrigation is cited as a strategy for enhancing income generation and food security for sub-Saharan Africa's poor farmers, but what makes this technology a successful poverty alleviation tool? In the short run, the technology should pave the way for increased consumption, asset accumulation, and reduced persistent poverty among users. Over the longer run, it should lead to institutional feedbacks that support sustained economic development and nutritional improvements. Our conceptual model and review of case studies reveal the importance of three sub-components of irrigation technology—access, distribution, and use—and the ways in which the design of the technology itself can either bridge, or succumb to, institutional gaps. These critical features are illustrated in an experimental evaluation of a solar-powered drip irrigation project in rural northern Benin, which provides a controlled study of technology impacts in the Sudano-Sahel. The combined evidence highlights the technical and institutional requirements for project success and points to two important areas of research in the scale-up of any small-scale irrigation strategy: the risk behavior of water users, and the evolution of institutions that either support or obstruct project replication over space and time.

Key words — Africa, Benin, irrigation, agriculture, crop diversification, solar technology

1. INTRODUCTION

(a) *The case for smallholder irrigation*

The poorest populations in sub-Saharan Africa live in rural areas and depend primarily on rainfed production of staple crops for their livelihoods. Yields for these crops are characteristically low and subject to weather-driven fluctuations, and production is typically limited to a 3–6-month rainy season. In addition to potential annual income and caloric shortages, smallholder dependence on staple production presents two seasonal challenges: first, households must stretch their stores of staples through the beginning of each rainy season to the next harvest (or purchase additional food, usually at higher prices); second, access to nutrients and micronutrients *via* home production or purchase is often significantly reduced during the dry season.

Smallholder farmers dependent on such seasonal staple production systems often face multi-scale poverty traps (Barrett & Swallow, 2006). At the individual level, these smallholders and their family members (defined here as the ultra-poor), typically survive on less than $1.25 per person per day and suffer from diminished nutritional status (Ravallion, Chen, & Sangraula, 2008). At the household level, they spend most of their incomes on food (Banerjee & Duflo, 2007; Zezza *et al.*, 2008) and many do not produce any surplus. Data from national household surveys in eastern and southern Africa show that only 1–3% of smallholders account for one-half or more of all staple grains sold commercially by the sector, and that only 20–35% of smallholders sell any grain at all (Jayne, Zulu, & Nijhoff, 2006). In addition to year-to-year consumption poverty, their households are asset-poor over time, with little to buffer the impacts of a particularly bad harvest year. At the village level, services that might facilitate a shift in well being for most smallholders—improved water sources, latrines, health clinics, schools, communications technologies, and energy services—are often lacking, and market availability and prices of calories, protein, and micronutrients show strong seasonal variation. Finally, at higher administrative levels, infrastructure and financial institutions are weak or non-existent, and entire regions or even nations may be both ultra-poor and net food-deficient.

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Against this backdrop of multi-scale poverty, the prospects for even the most entrepreneurial smallholders can seem grim: since farmers are asset-poor, marginal changes in productivity in low-valued staple crops at the household level are unlikely to facilitate an economic shift to a higher-level equilibrium. Markets for staples in sub-Saharan Africa tend to be very price-inelastic, so fluctuations in productivity result in widely varying prices (Jayne *et al.*, 2010). At the village and regional levels, the lack of market connectivity and adequate storage facilities results in local price slumps at harvest time, when many of the poorest households are most in need of income. The combination of local market isolation, weak infrastructure, price inelasticity, and a general sense of hopelessness among persistently poor households creates disincentives to adoption of productivity-enhancing technologies (Carter & Barrett, 2006; Jayne *et al.*, 2010; Vitale & Sanders, 2005). Moreover, the macro- and meso-scale deficiencies feed back to reinforce low productivity and poverty at the micro scale.

This paper explores the role small-scale irrigation technologies might play in breaking the cycle of low productivity and precipitating a sustainable escape from persistent poverty in sub-Saharan Africa. The promotion of irrigation is frequently cited as a strategy for reducing poverty and improving food and nutrition security in the world's poorest regions (Keller & Roberts, 2004; Magistro *et al.*, 2007; Polak & Yoder, 2006; World Bank, 2007). As Asia's Green Revolution demonstrates, irrigation, when combined with the availability of inputs (fertilizer) and improved crop varieties, can enable year-round cultivation and promote increased yields. From a technical perspective, national- and regional-level estimates suggest that Internal Renewable Water Resources (IRWR) are significantly underexploited in much of sub-Saharan Africa. For example, data from the FAO AQUASTAT database show that the Gulf of Guinea region (coastal West Africa) uses 1.3% of its IRWR, and the entire Sudano-Sahel uses only 35% of its IRWR (Frenken, 2005).

Perhaps most importantly, irrigation facilitates the introduction of new crops in regions where they could not be sustained by rainfall alone. Many rural areas in the dry tropics face a chronic shortage of vegetable and fruit crops, particularly during the dry season (as evidenced by household consumption surveys, e.g., Smith, Alderman, & Dede, 2006). Excess local demand (i.e., elastic local markets) means that markets are not prone to saturation; prices for such crops remain relatively high year-round, and farmers can cultivate numerous high-value crops and tailor their cropping calendars in response to local conditions (Jayne *et al.*, 2010). Diversification into high-valued crops may be particularly important for poverty alleviation in sub-Saharan Africa given the evidence of declining *per capita* land holdings across the continent (Food and Agriculture Organization of the United Nations, various dates; Jayne *et al.*, 2003, 2006; Nagayets, 2005), and the volatility in staple crop prices worldwide. Previous research has shown that the trend toward diversification is inversely related to land holding size in several parts of southern and eastern Africa (Jayne *et al.*, 2010). It is possible, therefore, that the use of small-scale water irrigation technologies to promote diversification among the poorest farmers could substantially improve returns to labor and land, reduce risks of production collapse in any given crop, and provide linkages to multiple (more elastic) local markets.

Given the recent attention to small-scale irrigation, and its potential as a poverty alleviation tool in rural sub-Saharan Africa, we ask three questions in this paper: Have adopters of small-scale irrigation been able to realize expected efficiencies—even in the presence of a learning curve—and if so, which irrigation technologies and cropping systems have been most promising? Do revenues from these systems lead to consumption changes, asset accumulation, and/or alternative investments (e.g., in education or land improvements)? And finally, is there any evidence for endogenous formation of institutions from these systems, such as the creation of land tenure or credit arrangements, which can support the use of distributed irrigation and high valued crops for smallholders over the long term? In exploring these three questions, we also question whether indigenous farmer groups might provide the minimal institutional framework necessary for irrigation to be a true poverty-fighting tool.

This paper addresses the above questions as follows: we first develop a conceptual model of successful technology adoption for smallholder farmers in sub-Saharan Africa, considering the physical components of different smallholder irrigation projects as variables upon which successful uptake will depend. This model derives from theory, empirics, and case studies described in the literature, including experience from a decade of drip irrigation projects undertaken across the Sudano-Sahel by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).[1] Second, we examine a case of successful smallholder uptake of solar-powered irrigation and crop diversification in northern Benin. This specific example differs from most case studies in the literature in that it is developed in a controlled framework to evaluate the technological, agronomic, and economic potential of high-quality drip irrigation technology applied to market gardens with a focus on ultra-poor households (Burney, Woltering, Burke, Naylor, & Pasternak, 2010). Like most case studies, however, it contains some bias in terms of favorable technology and institutions, and the risks to adopters are veiled in this pilot phase of implementation. Nonetheless, our experimental analysis highlights the project factors—technological and institutional—that have both enabled significant improvements in farmer well being and spurred growth of local institutions.

2. CONCEPTUAL FRAMEWORK FOR EVALUATION OF SMALLHOLDER IRRIGATION PROJECTS

In general, as shown in Figure 1, a smallholder irrigation system can be conceived as an aggregate of three components: a water *access* technology, or a method of moving water from its source; a water *distribution* technology, or a method of spreading water; and a *use*, or a productive water application. Access technologies include all pumps—from human-powered rope and treadle pumps to liquid fuel engine-driven systems to solar-powered pumps—and enable access to water where it was previously unavailable. Distribution technologies facilitate distribution of water (and fertilizer) to plants at the plot level, and include simple furrows, watering cans, micro-sprinkler systems, and drip irrigation systems (both low-cost and conventional). Both access and distribution technologies can increase returns to labor, and may also provide direct cost savings in cases where farmers pay for energy services and/or water. Finally, productive water applications include the use of higher-yielding varietals with inputs (e.g., fertilizers) for crop diversification and production of high-value crops. These water use technologies increase returns to land and irrigation investments. Since the term "smallholder irrigation" has come to include systems that draw water from various sources, and use different access and distribution technologies to irrigate different types of crops under different management practices, it is critical to understand the specific functionality of a given irrigation system. For example, a smallholder irrigation project that focuses on hand-watered vegetable plots (using a well and watering cans) will have different economics, different

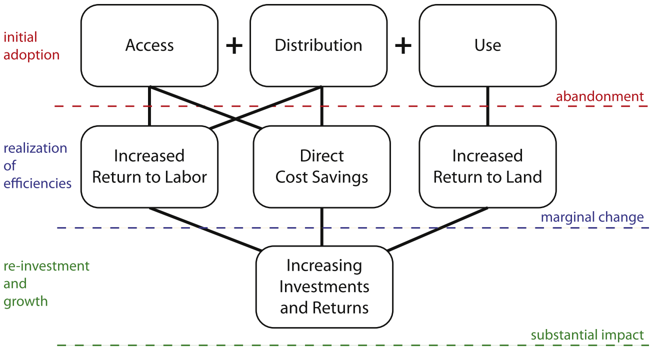

Figure 1. *Schematic of smallholder drip irrigation system components and pathways of impact. We conceptualize a smallholder irrigation system as an aggregate of three sub-components: a water access technology (e.g., bucket, pump), a water distribution technology (e.g., watering can, drip irrigation kit), and/or a productive application (e.g., high-value crops, improved varieties). A water access technology facilitates water use where it may have been impossible or at an improved efficiency, which translates into labor or cost savings. A water delivery technology enables efficient water use, and subsequent labor or cost savings. A productive application technology increases returns to land via higher yields and/or crop values. This conceptual model suggests that project successes and failures can be assessed in three sequential periods—adoption, realization of efficiencies, and re-investment—and that three possible outcomes exist: An irrigation system would likely be abandoned (and thus considered a failure) if the adopter were unable—for any reason—to realize the efficiencies afforded by new access, delivery, and/or use technologies. An irrigation system would be an instrument of marginal change if such efficiencies are achieved but do not kick-start a greater cycle of investment and prosperity. Finally, a smallholder irrigation system has substantial poverty impact only if the adopter realizes significant efficiencies and is able to reinvest the subsequent labor and cost savings, starting up the ladder of increasing investments/returns and asset accumulation.*

requirements for success, and different impacts than a smallholder irrigation project that uses a motorized pump and furrow irrigation for rice production.

A variety of smallholder water access and distribution technologies are summarized in Table 1; in general, they do not require large infrastructure investments (e.g., canal systems) or their accompanying institutions (e.g., water management boards). They are, therefore, particularly appealing to development organizations and governments in that they can benefit lower income individuals or small user groups provided that the institutions governing water access and use exist at the community scale (Magistro *et al.*, 2007; Meinzen-Dick, 2007). Not surprisingly, smallholder irrigation is now the fastest growing type of irrigation in Africa (Frenken, 2005).

However, these schemes have met with varying success, and most current evidence on their performance has been anecdotal. Satisfied users claim to have doubled or tripled their incomes, while dissatisfied users cite a host of causes for failure, including unreliable water access, inadequate institutions for water allocation at the community level, equipment failure and inadequate supply chains, underwhelming labor and productivity gains, lack of agronomic support, and marketing problems (more below). In light of these claims, assessing small-scale irrigation as a poverty-reduction strategy requires specific attention to two key factors: the design of the technology itself, and the institutions that support the technology.

(a) *Technology design*

Any evaluation of a smallholder irrigation project should begin with the physical system components (access, distribution, and use technologies). Both synergies and dependencies exist between the three sub-technologies, and although a project may explicitly include only one (or two) of the three, it implicitly depends on (or assumes the existence of) the others. For example, a water access technology is not used economically with an inefficient distribution system or low returns to land and labor (e.g., in the form of staple crops); a water distribution system is useless without water access; and high value crops require consistent water access and reliable water distribution. The fact that smallholder irrigation systems do not all physically function in the same way highlights the importance of factor availability for project success. A project that promotes standalone low-cost drip irrigation kits without providing water access technology beyond hand-hauling assumes that users can ensure their own reliable access to water, including perhaps ample labor. Conversely, a project that promotes liquid fuel-based pumps for access with no distribution technology beyond hand spreading of irrigation water assumes that users have reliable access to fuel and maintenance services, and that the farmer does not see the cost of less efficient water use. Finally, any new technology has an associated learning curve—a period characterized by inefficiencies and lower realized gains. Introducing access, distribution, and use technologies together may increase the likelihood that a farmer survives the learning period with sufficient gains to reinvest.

(b) *Institutional context*

A second key component for evaluation encompasses the institutional linkages assumed, leveraged, and/or created by a given project. The institutional environment surrounding a smallholder irrigation project will necessarily impact the likelihood of project success, from initial adoption to re-investment and growth. Institutions can be conceived as incentive structures formed by society that determine economic performance and social interactions; they are comprised of formal and informal modes of conduct (rules and laws, norms and conventions), enforcement mechanisms, and a dynamic aspect that leads to learning-by-doing and institutional evolution (North, 1990, 2005; Ostrom & Basurto, 2011). For example, farmer organizations, credit programs, and land tenure arrangements are all institutions that can help individual farmers overcome the barriers to initial technology uptake. Likewise, institutions for insurance and risk-spreading, technical support, market access and information, and education can help adopters survive the "learning curve" period associated with a new technology and reap adequate returns to facilitate re-investment. Finally, the existence of local or regional supply chains, information technologies, education, and financial institutions can provide an adopter with opportunities to enhance farm income, re-invest, and grow.

The institutions that organize the allocation and use of water in irrigation systems vary by scale, region, and adaptive capacity and greatly influence the successful adoption of irrigation technologies (Meinzen-Dick, 2007; Ostrom & Basurto, 2011). There is no single institutional structure that works across the developing world to facilitate the management of irrigation water. An early World Bank technical paper on irrigation found that, across the countries of the Sahel, projects that involved private farmers or leveraged autonomous farmer groups (formal and informal) were more likely to be successful than those undertaken with larger water user associations and cooperatives (Brown & Nooter, 1992). Small-scale irrigation systems, which typically build on historical community relationships and avoid the need for new water-user associations,

Table 1. *Components of smallholder irrigation systems—water access and distribution technologies*

Water access technologies extract and move water from a source:

- Water may be hand-carried by bucket, basin, or jerry can from a well or surface source
- Treadle pumps are human-powered pump that uses a stepping motion to generate the pressure to extract water from up to 7 m depth (~1 L/s). Treadle pumps were developed in the late 1970s in Bangladesh, and have spread through Asia and Africa since the 1990s largely through the work of organizations like International Development Enterprises (IDE) and KickStart
- Motor pumps use gasoline, kerosene, or diesel fuel to power a centrifugal pump. The lowest-cost varieties can extract water from 5–10 m depth, and use approximately 0.15 L of fuel per m^3 of water pumped
- Solar pumps use photovoltaic arrays to power either surface or submersible pumps, across a large range of depths

Water distribution technologies spread water across the field:

- Direct flooding (large plots) and hand pouring (small plots) are the most basic forms of distribution
- Furrows (for large plots) and watering cans (small plots) improve spreading speed efficiency over flooding or pouring
- Sprinklers spray water across the field surface, improving speed and efficiency
- Drip irrigation kits use a series of tubes and emitters to distribute water (and soluble fertilizer) directly to individual plants, thereby achieving water savings of up to 50%. Modern drip irrigation was developed in Israel in the late 1960s and spread widely across large farms in the United States, Europe, and Australia. These systems feature pressure-regulated emitters which enable uniform water distribution over very large areas. In the developing world, conventional drip irrigation refers to smaller versions of this type of system, in which water is fed to the drip lines *via* concrete reservoirs or oil drums, from a height of 1–3 m. In the 1990s, low-cost drip irrigation was developed and popularized by IDE. These systems do not have pressure-regulated emitters and therefore cover smaller areas; they are usually fed by oil drums, buckets, or even hanging bags at 1–2 m height

		Lifetime (years)	Price (USD)
Water access technologies	Bucket, *etc.* (labor not included)	2–3	5
	Treadle pump (labor not included)	2–5	20–100
	Motor pump (fuel/lubricant not included)	3–8	300–1500
	Solar pump	15–25	3,000–10,000
Water distribution technologies	Watering can (labor not included)	2–3	15–25
	Low-cost drip irrigation kit	1–3	50–100 per 1,000 m^2
	Conventional drip irrigation kit	5–10	1500–2500 per ha

Water harvesting and other methods to increase soil moisture for a given plot are not included in this framework

thus appear more promising than large-scale irrigation systems in the sub-Saharan context.

Together, technology design and institutional context influence whether or not small-scale irrigation systems will benefit ultra-poor agricultural households. The extant literature is rife with examples of failures of the ultra-poor to fully benefit from smallholder irrigation technologies. Early work in Asia (Shah, Alam, Kumar, Nagar, & Singh, 2000) suggested that low-cost irrigation technologies (like treadle pumps) self-selected low-income adopters, but more recent work suggests the opposite: studies of adoption in both Asia and Africa have shown that successful adopters are often *not* the poorest agricultural households (Mangisoni, 2008; Namara, Upadhyay, & Nagar, 2005) and that even aid and development projects often fail to target the poorest households (Belder, Rohrbach, Twomlow, & Senzanje, 2007). Even if an irrigation system is adopted by a poor farmer, inputs may not be allocated optimally to irrigated land, particularly if gender relations are unbalanced (Udry, 1996) or if farmers fail to balance investments in divisible (fertilizer and seed) and lumpy (irrigation and capital equipment) technologies (Feder, 1982; Feder, Just, & Zilberman, 1985). Finally, the lowest income adopters are likely to reap lower returns to their investments in irrigation as a result of low education (van de Walle, 2003), and will benefit less from social learning than wealthier farmers (Foster & Rosenzweig, 1995). As a consequence, the poorest farmers are vulnerable to more substantial inefficiencies during the learning period and are less likely to use technologies successfully even if they manage to adopt them. Thus, when considering the potential for irrigation to improve the livelihoods of the world's poorest agricultural producers, it is critical to widen the scope of analysis to include access, distribution, and use technologies—and their institutional dependencies and linkages—to understand what works and why.

3. REVIEW OF SMALLHOLDER IRRIGATION EXPERIENCE IN SUB-SAHARAN AFRICA

We use the above framework to assess the existing smallholder irrigation case studies in sub-Saharan Africa. The importance of considering specific smallholder irrigation components and technological-institutional dynamics in project success is illustrated in several notable evaluations of projects that explicitly incorporated only one or two of the access-distribution-use triad of technologies described in Figure 1. Most of these projects targeted individual farms as opposed to cooperative farming systems in which farmers share costs, risks, and knowledge. For example, a 2002 study in Kenya surveyed 16 private adopters of standalone low-cost drip irrigation systems, and 19 individuals who had discontinued use of the kits (Kulecho & Weatherhead, 2005). While not a controlled study, the authors found that the systems had a high technical failure rate (57%), and in the absence of technical support, the majority of dis-adoptions occurred in the first 2 years. Beyond technical problems, the primary factor driving dis-adoptions was water: respondents either did not have reliable access to water (or no water access technology) or their plot lay so close to an easily-accessible water source that the efficiencies afforded by the drip kits (particularly when combined with new maintenance requirements) were not felt.

Even the explicit incorporation of a productive use component cannot necessarily offset issues of access. Between 2002 and 2006, 70,000 drip irrigation kits (75% low-cost, 25%

conventional) were distributed in Zimbabwe as part of humanitarian relief efforts, along with vegetable seed packs, introductory training, and in some cases fertilizer (45% of beneficiaries). Studies to determine the impact of these irrigation packages yielded disappointing results (Belder, Rohrbach, Twomlow, & Senzanje, 2007; Moyo, Love, Mul, Twomlow, & Mupangwa, 2005). In a study of 232 beneficiaries and 85 non-beneficiaries over 14 districts, the authors found that dis-adoption occurred rapidly, with only 16% of kits still in use after 3 years. As in the Kenya study, many dis-adoptions were due to technical problems (particularly clogging) and unreliable access to water: the further the water source from a household's plot, the more likely that the drip kit would be abandoned. Households still using the kits often did not understand how to check soil moisture conditions and added supplemental water by hand to see surface moisture, negating the efficiencies afforded by drip irrigation. Given the rate of abandonment, authors concluded that the low-cost drip irrigation kits were an effective technology only when used as a stepping stone to purchase higher-cost and higher-performance conventional systems (which performed better in the field) or motorized pumps (as the largest labor costs for these smallholder systems lay in the water access, hauling over long distances).

Although standalone water distribution technologies like drip irrigation kits are often limited by lack of water access, standalone water access technologies do not necessarily fare better. After heavy government and NGO promotion of treadle pumps in Malawi through various gift and loan schemes, one evaluation surveyed 50 adopters and 50 non-adopters in two districts in 2004 and 2005 to assess poverty and food security impacts of the irrigation technology (Mangisoni, 2008). The authors found that, while adopters were less vulnerable to seasonal consumption poverty, water shortages still posed problems, particularly for groups of farmers that had come together to jointly purchase a treadle pump. Furthermore, some users complained that the plot size irrigable with one treadle pump was too small, but purchasing a second pump was financially impossible. A similar study of 52 private adopters and 56 non-adopters in two regions in Ghana in 2005 showed that net farm income for treadle pump adopters increased compared to non-adopters, and that these adopters put their new income toward school fees, health expenditures, businesses, and assets (Adeoti, Barry, Namara, Kamara, & Titiati, 2007). However, adopters were more likely at the outset to have lower dependency ratios in their households and greater access to extension services, indicating that in the private Ghanaian market, the poorest households still have lower economic and institutional access to productivity-enhancing technologies.

As the case studies above indicate, smallholder irrigation projects in sub-Saharan Africa have often lacked emphasis on the use component, and any farmer gains thus came from extension of the growing season or simply being able to cultivate a larger area (Adeoti, Barry, Namara, Kamara, & Titiati, 2007; Moyo, Love, Mul, Mupangwa, & Twomlow, 2006). By contrast, the experience of smallholder irrigators in Asia (e.g., India and Nepal) underscores the importance of high-value crop (especially vegetables) production for irrigation to be a successful growth promotion tool. International Development Enterprises (IDE) has promoted and popularized the development of very low-cost water access and distribution technologies in these areas (Magistro *et al.*, 2007; Polak, Nanes, & Adhikari, 1997; Polak & Yoder, 2006), and their success bolsters much of the hope for smallholder irrigation systems elsewhere. But farmers in many IDE regions had access to and autonomously undertook production of higher-value crops with their new low-cost access and distribution systems (i.e., the use component was assumed). The ability to generate greater returns to land (*via* higher-value crop production and improved yields) is ultimately what makes water access and distribution technologies economically viable and allows farmers to survive the learning curve. Given that sub-Saharan Africa has the fastest declining *per capita* land holdings in the world (Food and Agriculture Organization of the United Nations, various dates.), increased attention to the use component for improved returns to land will be even more critical.

(a) *The African Market Garden*

Studies of autonomous evolution of farming practices like the ones described above provide powerful evidence of the connectivity between use and water access/distribution technologies; these are underscored by the experience of horticulture-based development projects. For example, in the past decade, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), in Niamey, Niger, has installed over 2000 drip irrigation systems, or "African Market Gardens" (AMGs) across the Sudano-Sahel. The various AMG projects have paired conventional drip irrigation kits fed by concrete reservoirs or oil drums with a variety of water access technologies, from shallow dams to artesian wells to solar-powered pumps (see Table 1). They have been implemented in 11 West African countries at a variety of scales and with various socio-institutional configurations, including individual systems, "cluster" models (a group of individual systems connected to a common water source), and "communal" gardens (shared systems divided into individual plots). In all of these cases, drip irrigation is applied to a diversified mix of market garden crops and installed as part of a larger management and training package that includes ongoing horticultural training and initial access to improved seeds. The African Market Garden technology and history are described in detail in earlier sources (Pasternak & Bustan, 2003; Woltering, Pasternak, & Ndjeunga, 2011); below we situate several AMG case studies in the conceptual framework described above.

The first installations in Niger (ICRISAT, 2003) focused on development of an equipment and management package that would be attractive to farmers already engaged in horticulture, particularly in areas near large urban vegetable markets. The project organized demonstration plots (pilot farmers) who signed contracts verifying that they had secure land and water access, could purchase the AMG system, would be open to receiving training and using new techniques, and would share their knowledge with other farmers. Upon seeing the pilot farms, 778 systems (188 × 500 m^2 and 590 × 80 m^2) were purchased by other farmers in the region. After one year of operation, only 60% of the kits were still in use, so ICRISAT technicians refined the training component to include repeat visits over the first several seasons of operation. Staff reported that the highest gains (and lowest rates of abandonment) were from full-time farmers, who often purchased more than one AMG system.

A subsequent project in Burkina Faso and northern Ghana (Iddal, 2007) focused on existing farmers in the areas surrounding three larger markets. These farmers (with similar requirements to the Niger project) opted to purchase 500 m^2 drip irrigation kits as well as improved vegetable seeds and training on horticultural methods. A total of 400 systems were installed, with some farmers in Burkina Faso creating groups to share reservoirs to cut costs. The project in northern Ghana utilized "cluster" systems, whereby each individual farmer in a group had his/her drip irrigation kit connected to the same shallow dam water source. In both Burkina Faso and Ghana, farmers realized large yield gains, on average doubled their revenues, and elected to continue with the technology.

Through these two large projects, the ICRISAT developed an irrigation and training package against a backdrop of established water access and market connectivity; this package, in turn, allowed for the tailoring of the technology for poorer producers (often women). In particular, the experience with cluster systems in northern Ghana and of self-organized reservoir sharing in Burkina Faso highlighted the role farmer groups might play in driving down startup costs, economizing on input purchases, spreading risk, facilitating training and knowledge transfer, and creating bargaining power in the marketplace. A subsequent pilot program in Burkina Faso featured 20 poor pilot farmers (5 women) who elected to purchase a subsidized 500 m^2 AMG package (Belemvire, 2007). These farmers had some water access, though not always ensured, and often *via* shared motor pumps that frequently broke. Nevertheless, the farmers realized expected gains over two years and paid school fees or bought new pumps and livestock with the revenues. Ninety percent decided to continue with the system.

The experiences from the series of AMG projects anecdotally support the idea that the combination of water access, efficient water delivery, and production of high-value crops results in synergistic gains; economic analysis of AMG systems in comparison with traditional watering can systems have shown increased returns to land, labor, and water (Woltering, Pasternak, & Ndjeunga, 2011). Water access and delivery systems may be conceived as technologies that facilitate the diversification into production of high-value crops (or, conversely, high-value crops make investment in labor- and cost-saving water access and delivery technologies economical). However, the existing literature highlights an important reality: while uptake of a water access technology may lead to the uptake of a water delivery technology, and *vice versa*, neither necessarily leads to uptake of high-value crop production (Pasquini, Harris, Dung, & Adepetu, 2004). For example, the projects in Ghana and Zimbabwe mentioned above showed no increase in crop diversification upon adoption of treadle pumps or drip irrigation kits, respectively. Evidence from a study of irrigation in Zambia (Hiller, 2007) showed that production of high-value crops increased with increasing value of water access technology (from bucket to treadle pump to motor pump), indicating that uptake of low-cost irrigation systems by smallholders does not necessarily lead to production of high-value crops.

Overall, evidence from the case studies described above suggests two important conclusions. First, any program that is based on water pumping or delivery systems that have fundamental technological weaknesses is a non-starter - - for example, pumps that break or cannot be fueled, drip irrigation lines that crack or clog excessively, or pumps located in places without adequate water resources for the agricultural system in question. While low-cost inputs are desirable in poor communities, they are not preferred and will typically be dis-adopted if they are short-lived and lead to disappointing productivity and income growth. This conclusion is particularly noteworthy in places with poor infrastructure, where the lower upfront cost of a shorter-lifetime access or distribution technology can be quickly offset by high transportation costs associated with replacement. Second, a key precursor to breaking the poverty trap with these technologies is inclusion of diversified high-valued market crops in the development package. The use component of the system appears to be neglected (or assumed) in many programs, yet it is essential for economic returns on investment, accessing multiple markets (thus stabilizing income flows), and increasing labor and land productivity over time.

4. EXPERIMENTAL ANALYSIS OF A SMALLHOLDER IRRIGATION PACKAGE FOR THE ULTRA-POOR

Building on lessons from these previous drip irrigation evaluations and AMG installations in West Africa, ICRISAT, an NGO partner (the Solar Electric Light Fund (SELF: http://www.self.org)), and a local CBO (l'Association pour le Developpement Economique, Sociale, Culturel, et l'Autopromotion, or ADESCA-ONG) began a novel solar- (photovoltaic)- powered drip irrigation project in the Kalalé district of northern Benin in 2007. The Solar Market Garden (SMG) project aims to boost vegetable production from communal gardens in an effort to combat high malnutrition and poverty levels throughout the year—and especially during the dry season when malnutrition is accentuated. In a broader sense, the project also aims to bring together the lessons learned from previous irrigation projects in assembling a technology and management package that might succeed for the ultra-poor against a very weak institutional background. To assess the impact, feasibility, and sustainability of the solar-based irrigation concept, we joined the project partnership to independently monitor and evaluate the installation and use of three 0.5 hectare SMG systems in two villages for two years beginning in November 2007. Although the SMG concept, initial impacts, and environmental and economic sustainability are described in detail in an earlier publication (Burney, Woltering, Burke, Naylor, & Pasternak, 2010), we briefly review the technology and experimental design here as prelude to the more in-depth analysis of welfare impacts described in this paper.

The SMG concept is a modification of the ICRISAT African Market Garden system designed for rural areas with no electricity access, where fuel supply is unreliable and fuel prices volatile or too expensive for smallholders. In a Solar Market Garden, a solar photovoltaic array powers a pump (either surface or submersible, depending on the water source) that feeds water to a reservoir; the reservoir then gravity-distributes the water to a low-pressure drip irrigation system. The system only runs during the day to avoid the use of batteries (energy storage is in the height of the column of water in the reservoir); local water availability and evapotranspiration needs inform the sizing of pumps, reservoirs, and fields. The system passively self-regulates: since solar radiation is the main driver of both pump speed and evapotranspiration, the volume of water pumped increases on clear hot days when plants need more water, and *vice versa*. The solar-powered pumps and conventional drip irrigation systems were combined with the high-value horticultural production training developed by ICRISAT in the previous AMG projects. In this way, the SMG system represents a top-of-the-line combination of access, use, and distribution technologies.

(a) *Solar Market Garden impacts over the first year of use*

To assess the success of small-scale irrigation technology among ultra-poor communities, we gathered an array of data before, during, and after the first year of system use to understand whether or not poor farmers could access the technology, benefit individually and collectively (as a community) from the technology, and use the technology as an engine for growth and institutional transformation. Here we present an analysis of short-run changes in incomes and consumption, and provide evidence of asset accumulation and alterations in household investment strategies. The analysis also demonstrates returns on investments to SMGs relative to other irrigation options (e.g., diesel-powered pumps) and assesses the ability of farmers to earn sufficient profits during the learning curve to make the technology sustainable at the household and farmer organization scales. In short, the analysis shows this technology can be implemented in an affordable manner and results in significant consumption impacts.

For the pilot assessment of this concept, three SMG systems were installed in two villages in conjunction with pre-existing local women's agricultural groups. Almost all of the villages in Kalalé have such groups, which engage in activities from vegetable production to collective harvesting of members' fields to value-added activities, depending on the group and village. The pilot villages were chosen from a larger subset of villages in which the women's agricultural groups were engaged in vegetable production; the goal was to address their water needs and to leverage their existing group infrastructure. The pilot villages were selected based on water source: the implementing NGO chose one with surface water and one with deeper groundwater to span the technical parameter space of the district. This non-random village selection, combined with the non-random membership in women's agricultural groups within each village, presents two potential selection biases that must be addressed in the analysis.

To address potential village selection bias, two "control" villages (from the original pool of candidate villages) were chosen for comparison with the pilot ("treatment") villages, based on proximity along a group of covariates—location along the same roads, administrative status, distance to the main town, water source for the women's agricultural group, and size. The control villages selected were the closest overall matches; baseline indicators for both treatment and control villages are presented in Table 2. To quantify the household impacts of the SMG technology, we conducted detailed household surveys just as farmers in the women's agricultural groups began using the systems in November 2007, at the beginning of the dry season. In each village (both treatment and control), both women's agricultural group members and a random, representative sample of village households were surveyed. (Women's agricultural groups in the control villages engage in market garden agriculture with hand watering, as had the groups in the treatment villages before intervention.) This research design allows for between- and within-village comparisons, addressing at least in part the potential selection biases at both village and agricultural group levels. The surveys were repeated with the same households in November 2008, after one full year of SMG use in the treatment group. (For further details on experimental design, see Burney *et al.* (2010).)

We constructed consumption aggregates from the survey responses using the methodology outlined by Deaton & Zaidi (2002).[2] To assess the impact of the SMG technology on these aggregates—as well as on other indicators of well-being—we calculate the difference in the change in these outcome indicators between treatment households (those with a member using the communal SMG system) and control households over time. We estimate these difference-in-differences coefficients *via* regression analysis, using two different models:

$$\text{Model 1}: \quad y_{it} = \alpha + (\beta_0 r_t + \beta_3 r_t w_i v_i) + x_i + \varepsilon_{it}$$

$$\text{Model 2}: \quad y_{it} = \alpha + (\beta_0 r_t + \beta_1 r_t v_i + \beta_2 r_t w_i + \beta_3 r_t w_i v_i) + x_i + \varepsilon_{it}$$

In both models, the outcome variable of interest for all households i, y_{it}, is regressed on indicator variables for time period and household project participation status: r_t indicates the time period for the survey (r is 1 for the follow-up, or post-treatment, survey and 0 for the baseline); v_{it} is 1 if a household is in a treatment village and 0 otherwise; and w_{it} is 1 if a household has a member in the village women's farmer group. The interaction term $w_i v_i$ is 1 for households that are both in treatment villages and in women's farmer groups; that is, the households using the SMG systems; and 0 otherwise. The coefficient β_0 thus gives the overall time trend for all households in the sample, and the coefficient β_3 represents the difference-in-differences estimator for project impact. To

Table 2. *Difference-of-means tests for control village matching using baseline data. The first set of columns compares treatment households to control households (i.e., non-women's group households within the treatment villages and all households in the control villages). The second set of columns compares women's group households to village households, across both treatment and control villages. The third set of columns compares treatment villages (women's group households and village sample) to control villages. Standard errors shown in parentheses. Asterisks indicate a difference of means significant at or above the 95% confidence level*

	Full sample comparison		Within village comparison		Across village comparison	
	Treatment households	Control households	Women's groups	Village sample	Treatment villages	Control villages
Total *per capita* daily CE, $PPP	0.89	1.12	1.16	0.98	0.94	1.20
	(0.10)	(0.06)	(0.10)	(0.05)	(0.06)*	(0.09)
Per capita daily food CE, $PPP	0.54	0.69	0.54	0.69	0.57	0.73
	(0.06)	(0.05)	(0.06)	(0.05)	(0.04)*	(0.06)
Per capita daily income, $PPP	0.42	0.47	0.48	0.44	0.41	0.51
	(0.14)	(0.08)	(0.11)	(0.09)	(0.11)	(0.08)
% of households under $1/day poverty line	86	73	74	79	80	72
Number of cattle	3.7	4.0	6.1	2.3	2.4	5.7
	(1.1)	(0.9)	(1.3)*	(0.6)	(0.6)*	(1.3)
Number of sheep and goats	6.8	6.8	7.9	5.9	5.1	8.6
	(1.2)	(1.0)	(1.3)	(0.9)	(0.7)*	(1.4)
Number of fowl	14.4	10.5	15.2	8.7	10.7	12.5
	(2.8)	(1.4)	(2.1)*	(1.4)	(1.8)	(1.7)
Total asset holdings, $PPP	53	103	60	113	88	92
	(6)	(17)	(5)*	(23)	(23)	(10)

control for the effects of inherent (time-independent) differences between households that might affect outcomes over time, we include household-level fixed effects, x_i. We calculate the coefficients for this model for three groups: (a) the entire sample, comparing all treatment households to all control households; (b) the subset of households belonging to women's agricultural groups across all villages, comparing women's group households in treatment villages to those in control villages; and (c) the subset of households in treatment villages, comparing project households to other households in the same village. These three tests compare the treatment households to three different control groups and thus offer some leverage in understanding potential selection biases at both the village and farmer group levels.

Model 2 is structured similarly to Model 1, but with two additional terms: the coefficient β_1 gives the simple effect of living in a treatment village over the first year of the project, irrespective of women's group membership, and the coefficient β_2 gives the simple effect of being in a women's agricultural group, irrespective of village. Again, household-level fixed effects (a dummy for each household) are included. Model 2, therefore, teases out the relative impacts of time, village, women's group membership, and SMG "treatment" simultaneously. This second model thus represents a very strict test of the impacts of the SMG technology.

The results of these two models (all four scenarios) are presented in Table 3. Overall, the story in these villages in northern Benin reflects the situation across much of the developing world during that time period: in 2008, rising food and energy prices were estimated to have pushed at least 100 million additional people worldwide into poverty (De Hoyos & Medvedev, 2008; Ivanic & Martin, 2008). Across all models, the time trend (β_0) shows a decline in living standards, in terms of consumption poverty (*per capita* daily consumption expenditure), number of households below the \$1.25 poverty line, and in terms of total asset holding value. Across all villages, households were more likely to rely on remittances, gifts, in-kind meals donated by others, and neighborly loans for meeting day-to-day needs. Fewer meals were prepared in homes, and households had less money to spend on energy services, including batteries, kerosene, and fuel.

In contrast, project households (those with a member with a share in one of the SMG systems), saw an increase in standard of living (β_3). The full model specification (Model 2) yields a \$0.69 *per capita* daily CE (USD \$PPP) difference between the treatment and control groups over time. Previously (Burney *et al.*, 2010), we showed that most of this difference went to food expenditures: project households purchased more food, across food groups and particularly in the dry season, than control households, giving strong evidence for improved annual and seasonal food security. This evidence is corroborated by changes in the household food insecurity score (a measure of ability to meet daily household food needs), which declined 17% for project households over control households. We also find that project households were less water insecure (more able to meet their daily water needs) than control households, although water access improved for all households over time.[3]

It is clear that over the first year of system operation, farmers using the SMG systems and their families benefited significantly from improvements in seasonal and annual nutritional intake and consumption expenditure. However, to understand the prospects for project replicability, sustainability, and longer-term development, consumption changes must be coupled with deeper, structural transitions. We therefore examined the data for evidence of impact beyond the short run: do families accumulate assets, and make investments, or does the SMG technology precipitate institutional changes that might alter structural poverty in the region?

During the first year of the project, there was no statistically significant evidence for asset accumulation for SMG users relative to the control group(s); however, unlike the other households, SMG users had a positive (if not quite significant) coefficient for number of animals and overall assets. This stands in contrast to the overall time trend (and trend for non-users), which was statistically significant and negative for asset and livestock accumulation across all villages. On average, all households in both the treatment and control villages tended to deplete their savings over the first year of SMG operation, which is consistent with the global poverty trends of 2008. Qualitatively, however, SMG users were much more likely than the control group to say that their households were better off than a year ago, giving further evidence for divergence between the two groups.

It is not necessarily surprising that SMG users did not show significant asset gains over one year, given the depth of many households' immediate and seasonal needs. There is reason to believe, however, that system users began to transition from meeting immediate and seasonal food needs to meeting other needs with their new income. For example, over one-third of the farmers stated in the baseline survey that they would use the proceeds from the garden to buy more food for their families. This number dropped by almost half in the follow-up survey. While there is not yet statistically significant evidence of increased school enrollment for SMG users' children, there is reason to think enrollment rates may rise in the near future. In the baseline survey, only 4% of farmers reported that they planned to use their earnings in the coming year to pay school fees for their children; after one year, this rose to 22%. Furthermore, there is no evidence that children are being kept out of school to work in the gardens. Farmers unanimously report spending less time working on their plots in the Solar Market Gardens than on their previous hand-watered plots, and only 24% report that anyone in their family ever helps them with their work. In addition to educational impacts on the next generation, the SMG systems seem to have promoted some numerical literacy within the women's agricultural groups: at project outset, only 1–2 farmers in each women's group had finished primary school and could read or write at all. Through the act of tracking sales and dues, however, some of the women (under the guidance of the literate few) have learned to write and (simply) calculate numbers.

The establishment of solar market gardens and their early success in one of the pilot villages has already led to complementary institutional developments in local education. Within a year of technological adoption, an elementary school curriculum was developed to help village children learn about the solar drip technology, labor savings from water access and delivery, and economic returns from high-valued vegetable production. When visiting the school and the gardens themselves, there was an overwhelming sense of pride in the new system by teachers, children, and women participating in the farmer groups.

In addition to educational impacts, the SMGs seem to have promoted institutional changes at the level of the farmer groups. First, while the land had been allocated to the women's groups traditionally (by a chief), the groups secured civil documentation for their land. Second, each group sought guidance and registered as an independent NGO in Benin during the first year of use. Although none of the groups has yet leveraged this new status for independent funding, it does qualify them to open low-fee bank accounts; each group has

Table 3. *Regression results for various indicators of well-being, with robust standard errors in parentheses and significance denoted by asterisks ($^{*}p < 0.100$, $^{**}p < 0.050$, $^{***}p < .010$). Regressions were run with household-level fixed effects and household clustered errors for all four models (simple treatment vs. control with all households, treatment vs. control only women's group households, treatment vs. control within treatment villages, and full difference-in-differences model accounting for women's group participation and treatment village location independently)*

	β_0 Time trend	β_1 Treatment village effect	β_2 Women's group effect	β_3 SMG project impact
Total per capita daily consumption expenditure, $PPP				
All treatment *versus* control households	−0.23			0.34
	(0.09)***			(0.19)*
Only women's groups (across villages)	−0.54			0.65
	(0.29)*			(0.33)*
Only treatment villages (within villages)	−0.16			0.27
	(0.11)			(0.20)
Full diff-in-diff	−0.12	−0.05	−0.43	0.69
	(0.10)	(0.15)	(0.30)	(0.39)*
Below poverty line (logistic regression)				
All treatment *versus* control households	0.96			−0.78
	(0.33)***			(0.74)
Only women's groups (across villages)	1.03			−0.85
	(0.56)*			(0.87)
Only treatment villages (within villages)	1.30			−1.12
	(0.75)*			(1.00)
Full diff-in-diff	0.58	0.71	0.44	−1.55
	(0.61)	(0.97)	(0.83)	(1.31)
Total per capita daily food consumption expenditure, $PPP				
All treatment *versus* control households	−0.06			0.26
	(0.07)			(0.14)*
Only women's groups (across villages)	−0.21			0.42
	(0.23)			(0.26)
Only treatment villages (within villages)	−0.05			0.26
	(0.09)			(0.15)*
Full diff-in-diff	0.02	−0.07	−0.24	0.49
	(0.09)	(0.12)	(0.25)	(0.29)*
Per capita daily income from in-kind food donations, remittances, and loans, $PPP				
All treatment *versus* control households	0.06			−0.04
	(0.02)***			(0.03)
Only women's groups (across villages)	0.08			−0.05
	(0.05)*			(0.05)
Only treatment villages (within villages)	0.09			−0.06
	(0.05)*			(0.05)
full diff-in-diff	0.03	0.05	0.05	−0.11
	(0.02)*	(0.05)	(0.05)	(0.07)
Number of meals prepared in household each day				
All treatment *versus* control households	−0.09			−0.06
	(0.06)			(0.11)
Only women's groups (across villages)	−0.52			0.37
	(0.12)***			(0.15)**
Only treatment villages (within villages)	0.06			−0.21
	(0.10)			(0.13)
Full diff-in-diff	0.02	0.05	−0.53	0.33
	(0.10)	(0.14)	(0.15)***	(0.20)
Food insecurity score				
All treatment *versus* control households	−0.03			−0.15
	(0.02)			(0.06)**
Only women's groups (across villages)	−0.03			−0.15
	(0.06)			(0.08)*
Only treatment villages (within villages)	−0.02			−0.16
	(0.05)			(0.07)**
Full diff-in-diff	−0.04	0.02	0.01	−0.17
	(0.03)	(0.05)	(0.07)	(0.10)*
Total per capita daily consumption expenditure for energy services, $PPP				
All treatment *versus* control households	−0.06			0.06
	(0.01)***			(0.04)

Table 3 (*continued*)

	β_0 Time trend	β_1 Treatment village effect	β_2 Women's group effect	β_3 SMG project impact
Only women's groups (across villages)	−0.02			0.02
	(0.03)			(0.05)
Only treatment villages (within villages)	−0.09			0.09
	(0.03)***			(0.05)*
Full diff-in-diff	−0.06	−0.03	0.03	0.05
	(0.01)***	(0.03)	(0.04)	(0.06)
Water insecurity score				
All treatment *versus* control households	−0.06			−0.11
	(0.03)*			(0.06)*
Only women's groups (across villages)	−0.09			−0.08
	(0.07)			(0.08)
Only treatment villages (within villages)	−0.01			−0.18
	(0.05)			(0.07)**
Full diff-in-diff	−0.10	0.11	0.01	−0.19
	(0.05)*	(0.07)	(0.08)	(0.11)*
Total asset holdings ($PPP)				
All treatment *versus* control households	−98.94			47.31
	(17.51)***			(18.56)**
Only women's groups (across villages)	−65.31			13.68
	(10.32)***			(12.04)
Only treatment villages (within villages)	−122.77			71.14
	(45.41)***			(45.82)
Full diff-in-diff	−97.71	−25.05	32.40	38.73
	(15.41)***	(47.85)	(18.53)*	(49.33)
Perception of conditions compared to previous year (Scale: 1–5)				
All treatment *versus* control households	0.10			1.63
	(0.14)			(0.24)***
Only women's groups (across villages)	1.57			0.16
	(0.18)***			(0.27)
Only treatment villages (within villages)	−0.45			2.18
	(0.22)**			(0.29)***
Full diff-in-diff	−0.29	−0.17	1.86	0.33
	(0.21)	(0.30)	(0.00)***	(0.41)

now opened such an account. Finally, the groups have each established their own revolving credit fund for input purchases and group investments; the magnitude of this revolving fund (~$1,000) is of a scale not typically available in the region, which has some microcredit access (typically ~$50–$100), and very little larger formal loan access. The women's group executive members have spoken of lending money to groups in other villages to begin vegetable production. As reported in the previous section, individual-based drip irrigation programs often report high rates of dis-adoption; group-based SMG systems, on the other hand, may provide the stability and institutional support necessary for the ultra poor to invest in production of high-value crops.

(b) *Economic sustainability, group-based implementation, and gender dynamics*

Based on revenue data from the first year of operation, we demonstrated earlier (Burney *et al.*, 2010) that the SMG system is cost-effective compared to the available liquid-fuel pump options when the cost of fuel is high and the cost per watt for the PV array shrinks (or the total overall power requirement is lower, as in a shallow groundwater application).[4] However, we note that, due to the higher up-front costs of a photovoltaic-based system and the lack of rural finance institutions providing credit in the "meso-scale" regime (~hundreds to a few thousand dollars), the technology is best suited for investment by farmer groups as opposed to individuals in very poor communities. As the Benin project and some of the case studies examined earlier involved farmer group beneficiaries, it is worth examining the role that such institutions might play in future irrigation projects.

Institutional barriers are often cited as the main obstacles preventing widespread uptake of irrigation technologies by the world's poorest populations; in this regard, leverage of existing local institutions like farmer groups may be an effective strategy to surmount these barriers. Institutional barriers include, for instance, a lack of access to credit and capital (as groups can economize purchases and apply for credit together), low education and illiteracy (groups can share knowledge and economize on training and extension visits), and low social stature of individual farmers, particularly women (groups can more easily share information, negotiate better prices, and economize on transportation to markets).

Nevertheless, the literature on farmer groups is mixed. The few existing studies of small-scale irrigation impacts in Africa have bolstered the notion that community-scale projects that leverage existing social structures for implementation can have significant individual and community impacts. For example, studies of community-based irrigation schemes in Senegal and Mali showed irrigation does boost overall household consumption and eliminates at least part of the seasonal component to malnutrition (Benefice & Simondon, 1993; Dillon, 2008). In some of the studies of autonomous technology adoption cited above, farmers grouped together to purchase various access, distribution, and use components. Finally, the ICRISAT African Market Garden experience with cluster and communal structures have leveraged existing farmer group structures for some of the highest success rates of AMG projects (Woltering *et al.*, 2011).

On the other hand, Mary Gugerty and Michael Kremer measure a negative impact of financial assistance on the organizational structure of women's agricultural groups in Kenya (they dub this the "Rockefeller Effect"). Their experimental design randomized the order in which the women's groups received training and inputs, allowing for use of the second set of groups to receive the training and inputs as a comparison for the first (Gugerty & Kremer, 2004, 2008). They found that the mere presence of resources attracted new members to the groups who were more likely to be younger, wealthier, and better educated (and sometimes male); this same type of member was more likely to be elevated to an executive position. Perhaps most worrisome, after receiving financial assistance, groups were more likely to expel older, less productive members. These women had presumably paid their inputs to the group in their younger more productive years and were now collecting on a form of social insurance; this type of women's group has long existed across much of Africa, is understood to be one of the few forms of collective bargaining power and social insurance for women, who are often marginalized by both social hierarchy and cultural marriage practices.

That the mere presence of resources changed the organizational structure of the women's groups so profoundly toward a patron-client dynamic gives pause: agricultural groups may indeed help surmount many institutional barriers to successful technology adoption and use, but the indigenous roles played by those groups may be altered in the process. Three years out, the Benin project has not seen the same effects as in the Gugerty and Kremer papers, but we remain aware of the potential for both positive and negative institutional impacts of group-based technologies, and our data indicate the need for more structured research on the interactions between women's groups (and farmer groups in general) and uptake of agricultural technologies.

More optimistically, we see early evidence for some of the benefits of group-based technology adoption in this project, with the women's groups securing formalized land rights and access to financial institutions, as noted above. In addition, some women have worked out a pair-based production system whereby one will produce seeds for use and sale, and the other will grow vegetables on her plot; they then share the profits from both, and lower their input costs. We also find evidence for knowledge-sharing, or the "shining star" model, whereby average production by farmers has approached maximum reported values over time, as shown in Figure 2. Three randomly selected women from each group were followed to assess production, sales, and home consumption levels over time. The seasonally-averaged (3 months) monthly reported production values for this group are shown in the main figure, with trend lines for the mean (blue) and maximum (green) values reported by the entire group. While the trend line for maximum reported value is essentially flat, the average production value has risen over time. In other words, the "shining stars" have maximized production from the start, but the average farmer has taken time to understand the system and optimize production (the "learning curve"). We believe that the upward trend is attributable to improved techniques; however, we would also expect to see the trend for maximum reported production rising in the future, as the farmers begin to plan their cropping calendars around market availability and pricing data that they have requested.

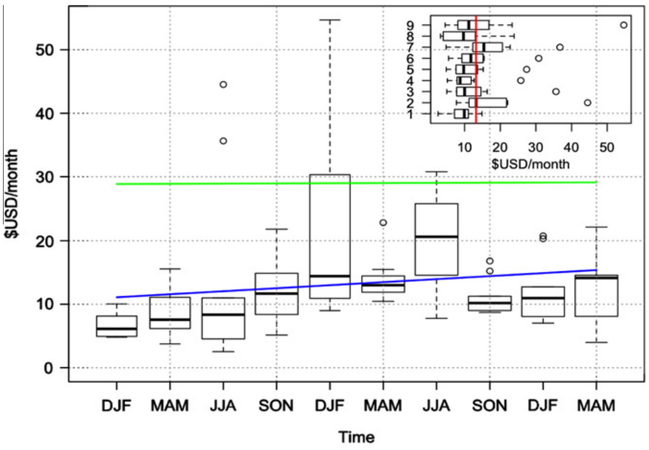

Figure 2. *Individual monthly revenues from SMG system users, December 2007–May 2010. Main figure shows three-month seasonal average monthly revenues from 9 women chosen randomly (3 from each group). Boxes show median (thick black line) and 25th–75th percentile, with whiskers indicating 5th–95th percentile range and circles denoting outliers. Blue line shows the fitted time trend for mean monthly production value for all women reporting ($y = \$10.62 + \$0.48 * \text{season}$), and green line shows the fitted time trend for maximum monthly values reported ($y = \$28.83 + \$0.03 * \text{season}$). Inset figure shows distribution for monthly production for the 9 women, with the red line giving the mean monthly production over time ($13.46).*

The magnitude of the gap between mean and maximum reported production on identical fields (producing similar product bundles) cannot be attributed alone to variance in expertise: women have also underreported their production over time, but are becoming better about reporting. Collection of accurate garden-level data has not been straightforward. Each group of farmers only has 1 or 2 women who can read and write; these women are usually the group secretaries, and are responsible for all group record-keeping, including production data. In interviews with project staff, large numbers of farmers admitted to underreporting—simply forgetting their notebooks, or not being in the garden at the same time as the secretary, and then forgetting to have her note it down later. The group secretaries also admitted to missing entire weeks of data collection (which is evident from entires). Beyond data collection issues, many women confessed that this was the first income they had ever earned (their production in hand-watered plots prior to project implementation had largely been for home consumption). Based on the rather sudden change in their income status, they did not want to share their earnings, even with group secretaries, for fear that the money would be taken or their home life would be upset.

A quick calculation corroborates the underreporting story. The coefficient for total *per capita* daily consumption expenditure between treatment and control households ($0.69) includes the net downward trend over the year for all households; the overall improvement in *per capita* daily CE for treatment households alone for the first year of irrigation use is around $0.11. As this amount is solely attributable to economic activity associated with SMG use, we can estimate the monthly production that would generate this amount, and compare it to reported values. Household size is 6–7 people for the women's group sample, so $0.11 per person per day corresponds to around $21 per women's group member per month, on average (sales and home consumption). As shown in Figure 2 (inset), average reported production over time for the subsample of women farmers is $13.46, or around 2/3 of the expected value. Our early hope was that, as these women become more comfortable over time in their income-generating roles, they would not hesitate to report their production accurately and completely. We additionally thought that the immediate links between the technology, education, and organizational stability might help enhance social sustainability through the acceptance, formalization, and promotion of the new system over time. Indeed, follow-up interviews with the women's groups in March 2011 confirmed that there is a wide variation in how open women's group members are with their husbands about their earnings; however, women across farmer groups unanimously agreed that their husbands were now very proud of their work and they felt more comfortable reporting to project staff.

5. CONCLUSION

Our review of small-scale irrigation projects in Africa and Asia suggests that the three components of an irrigation system—water access, water distribution, and water use—play complementary roles and will not necessarily be adopted autonomously. Experimental examination of the Benin case shows that a project combining access, distribution, and use can have high returns in the short run, including at the institutional level—potentially becoming a "game changer" for agricultural development over time. Nevertheless, questions remain about how such a project might be successfully replicated across the region and sustained over time.

Three related principles to guide future smallholder irrigation projects emerge from this analysis. The first is that the conventional notion that "cheaper technology is better" for the ultra-poor may not be true against a weak institutional backdrop like that found across much of rural sub-Saharan Africa. Although there are success stories of farmers starting with low-cost technologies and then moving up the ladder to invest in higher quality irrigation systems (e.g., Hiller, 2007), it is important to recognize that low-cost technologies are not without risk. Lower-cost technologies may fail to kickstart a cycle of increasing returns and investments in three ways: (a) local externalities like high transportation costs (added to repair or replacement expenses) or volatile energy supplies can easily dwarf startup costs and may ultimately favor higher-cost, longer-lifetime products; (b) technologies that facilitate only marginal efficiency gains may result in dis-adoption due to insufficient economic returns during the initial learning period; and (c) if driving down up-front costs comes at the expense of exclusion of one of the access-distribution-use axes, the tradeoff my not be favorable, given the assumed institutional support that comes with omitting one of the three components. Novel higher-cost technologies like Solar Market Gardens may thus counterintuitively be the most appropriate in certain localities, from both a technical and institutional perspective. Given projected climate changes across sub-Saharan Africa during this century (Battisti & Naylor, 2009; Held, Delworth, Lu, Findell, & Knutson, 2005; Lobell *et al.*, 2008), solar-based technologies and technologies that use water efficiently will almost surely become more valuable over time, the combined access–distribution–use system and farmer group-based implementation may help overcome institutional barriers for wide-spread adoption, and the novelty of such technology itself can inspire community organization (on top of household impacts).

The second conclusion relates to the cropping system: based on our case study review, access and distribution systems do not automatically precipitate a successful transition into production of high-valued crops, yet crop diversification is the component of a smallholder irrigation system with the most promise to dismantle the poverty trap structure at multiple scales. At the individual level, high-value crop production achieves increased returns to land for farmers, which is becoming increasingly important under tightening land constraints. At the individual and village levels, high-value vegetable production increases local food nutrient and micronutrient supplies. In addition, diversification into high-value crop production can transcend certain institutional barriers to smallholder production by providing a natural mechanism for risk spreading and linking a smallholder farmer to a broader array of markets. Demand for fruits and vegetables is much more elastic than for staples at local scales, so production of these commodities can have large household- and local-level impact in the short term without the need for pre-existing storage mechanisms, long-range transport capacity, and linkages to export markets. (Although ensuring market access for high-valued outputs at local to regional scales will be critical for success of such projects over the long run.) Nevertheless, further promotion of this cropping strategy—particularly when linked to novel, small-scale irrigation technology—requires more research on the risk behavior of smallholders in different regions. Specifically, there is a need to understand risk behavior in individual and farmer group settings with respect to uncertainties surrounding groundwater and surface water availability, market saturation, capital equipment failures, input prices and availability, and fuel prices for liquid fuel-powered irrigation pumps.

Third, interactions between technology design and institutional context need to be considered in any locality, both for potential pitfalls (e.g., assumed water access) and potential synergies. Institutional weakness is often cited as a reason for technological failure; institutions are thought to be preconditions for success in any development project. Our research suggests that well-designed small-scale irrigation systems can nevertheless bridge some institutional gaps and even induce new institutions to emerge in support of the technology. For example, small-scale irrigation systems obviate the need for large infrastructure projects, water boards, and other functional bureaucracy. When targeted at farmer groups, even high-end technology becomes divisible and more accessible to ultra-poor families (even in the absence of financial institutions); farmer groups can facilitate the sharing of risks, costs, and knowledge. By facilitating the production of higher-value commodities, an irrigation system can dramatically alter returns to land and labor for a household, freeing both time and capital for investment. Our experimental case in northern Benin—even in the short term—reveals the development of supporting curricula in local schools, the spread of shared learning in women's agricultural groups, and the formation of NGO entities by women's groups to establish rights to land and credit. Local leadership has also positively reinforced technology adoption and technology-institution linkages in the project villages. (We recognize that this is not always the case, and that local leadership can work in both positive and negative directions.) More generally, institutions surrounding water use and irrigation technology vary over space and time and cannot necessarily be replicated. As such, identifying appropriate institutional settings for widespread technology adoption and long-run success will require a more nuanced approach that builds on diagnostic techniques and adaptive learning (Meinzen-Dick, 2007; Ostrom & Basurto, 2011).

The most important question is: once project sites for small-scale irrigation and high valued crops have been established and show clear short-run success (as in the Benin study), how can they be scaled up across the region to promote a longer-run development strategy? The key issues that will determine the success of irrigation investments in the region (and in sub-Saharan Africa more generally)—in addition to institutional arrangements—include targeted users, market access, and economic sustainability of the technology. Irrigation technology is not likely to alleviate persistent poverty if it is not directed toward very low-income, smallholder farmers and if it does not generate sufficient financial (or private) net returns to make it profitable over the long run. Part of the scaling might take place through the types of endogenous institutional development mentioned in the Benin case. But the scaling process is likely to be much more successful if governments invest in meso-scale credit for farmers associations and regional traders of horticulture crops (not just micro-credit for poor, individual farmers); in transportation infrastructure and information technologies; and in education, including the vocational skills needed to support higher performance irrigation technologies (like those based on renewable energy sources). A single policy strategy that relies on investments in small-scale irrigation alone will almost surely fail over time.

Releasing smallholder farmers in Africa from persistent poverty in the coming decades will require a substantially new vision of agricultural development. Collier and Dercon argue that perhaps the international community is thinking too much about the smallholder sector, and that it might be time to think about larger-scale agricultural development and a massive migration out of agriculture by ultra-poor households (Collier & Dercon, 2009). We agree that the time has passed for nudging marginally productive technologies along for the smallholder sector, but we have a more optimistic view: well-designed irrigation technologies can generate income, promote food security, bridge institutional gaps, and bolster local institutions. Widespread dissemination of such systems to smallholders in Africa may be just what is needed to break the multi-scale poverty trap.

NOTES

1. To our knowledge, the published and gray literature on small-scale irrigation in Sub-Saharan Africa have not been reviewed comprehensively. This literature review thus represents an important contribution to understanding the successes and failures of small-scale irrigation projects.

2. In general, consumption is a more reliable indicator of the standard of living than income for poorer households, whose income tends to be lumpy, variable, and at least partially non-monetized. The Consumption Expenditure aggregate is the sum of the value of food consumed by a household (both purchased food and food produced by the household), regular non-food expenditures (education, health, household items, fuel, *etc.*), the rental equivalent of household durable goods, and housing expenditures (rent and utilities).

3. Alternative formulations of Model 1, combining difference-in-differences with propensity score (nearest neighbor, radius, and kernel) or Mahalanobis matching yield similar results across all three groups. This is not surprising, as the control households are a random, representative sample of the treatment and control villages. The agreement nevertheless provides an additional validity check on control village selection, at both the village and women's group levels.

4. This investment analysis is at the individual garden (SMG) level, and includes all capital equipment, installation costs, maintenance, training, and inputs over the lifetime of the solar panels (conservatively estimated at 15 years). Startup costs are up to ~$450 per person, with annual inputs/training/maintenance ~$140 per year. Payoff time is between 2 and 3 years. The cost-benefit analysis does not include programmatic costs for implementing organizations, although such figures will become very important during scale-up.

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