Solar-powered drip irrigation enhances food security in the Sudano–Sahel

Jennifer Burney[a,1], Lennart Woltering[b], Marshall Burke[c], Rosamond Naylor[a], and Dov Pasternak[b]

[a]Program on Food Security and the Environment, and Department of Environmental Earth System Science, Stanford University, Environment and Energy Building, 473 Via Ortega, Mail Code 4205, Stanford CA 94305-4205; [b]International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), BP 12404, Niamey, Niger; and [c]Department of Agricultural and Resource Economics, University of California, 207 Giannini Hall, Berkeley, CA 94720

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Meeting the food needs of Africa's growing population over the next half-century will require technologies that significantly improve rural livelihoods at minimal environmental cost. These technologies will likely be distinct from those of the Green Revolution, which had relatively little impact in sub-Saharan Africa; consequently, few such interventions have been rigorously evaluated. This paper analyzes solar-powered drip irrigation as a strategy for enhancing food security in the rural Sudano–Sahel region of West Africa. Using a matched-pair comparison of villages in northern Benin (two treatment villages, two comparison villages), and household survey and field-level data through the first year of harvest in those villages, we find that solar-powered drip irrigation significantly augments both household income and nutritional intake, particularly during the dry season, and is cost effective compared to alternative technologies.

photovoltaic | poverty | agriculture | water use | Africa

Significant fractions of sub-Saharan Africa are considered food insecure, as measured by total per capita caloric availability at the national level, consumption at the household level, and/or various individual nutritional status indicators (1, 2). Across the region, these food-insecure populations are predominantly rural, and they frequently survive on < 1 per person per day. Although most are engaged in agricultural production as their main livelihood, they nevertheless spend 50–80% of their income on food, and are often net consumers of food, particularly nonstaples (3).

Most rural, food-insecure communities in sub-Saharan Africa rely on rain-fed agriculture for production of staple crops, which is limited to a 3–6 month rainy season in the Sudano–Sahel [only 4% of cropland in sub-Saharan Africa is irrigated (4)]. On top of potential annual caloric shortages, households face two seasonal challenges: They must stretch their stores of staples to the next harvest (or purchase additional food, often at higher prices), and access to micronutrients via home production or purchase diminishes or disappears during the dry season. Typical smallholder staple production systems are often both risky and relatively low-return, as the low commercial value of staple crops is exacerbated by poor yields and erratic rainfall—two problems that are expected to worsen in the next few decades under climate change (5, 6). Promotion of irrigation—and particularly smallholder irrigation—is therefore frequently cited as a strategy for poverty reduction, climate adaptation, and promotion of food security (7, 8).

The role of irrigation in poverty reduction has been studied extensively in Asia [e.g., (9)], but relatively little has been written about the poverty and food security impacts of smallholder irrigation in the Sudano–Sahel. Access to irrigation water via engine pump increased both household savings and informal social insurance in the form of transfers in northern Mali (10); year-round vegetable production facilitated by canal irrigation in northern Senegal increased intake of vitamins A and C and decreased the incidence of emaciation among adults and older children (11).

Currently, drip (or micro) irrigation is the most rapidly expanding type of irrigation in sub-Saharan Africa (12). Drip irrigation delivers water (and fertilizer) directly to the roots of plants, thereby improving soil moisture conditions; in some studies, this has resulted in yield gains of up to 100%, water savings of up to 40–80%, and associated fertilizer, pesticide, and labor savings over conventional irrigation systems (13–15). Through private purchase, government programs, and non-governmental organization (NGO) projects, more and more smallholder producers are gaining access to low-pressure drip irrigation kits that require only 1 m of pressure to irrigate plots of up to $1,000\ \mathrm{m}^2$. Nevertheless, the impact of this technology has been limited in sub-Saharan Africa by reliable access to water, as well as lack of agronomic and marketing support (16–18).

Photovoltaic- (or solar-) powered drip irrigation (PVDI) systems combine the efficiency of drip irrigation with the reliability of a solar-powered water pump. As with any water pump, solar-powered pumps save labor in rural off-grid areas where water hauling is traditionally done by hand by women and young girls (19). They can be implemented in an easily maintained, directly coupled (battery-free) configuration, thereby avoiding one of the major pitfalls of photovoltaic (PV) use in the developing world (20). Though PV systems are often dismissed out of hand due to high up-front costs, they have long lifetimes, and in the medium-term, cost less than liquid-fuel-based pumping systems, particularly in areas where stable access to fuel is limited (21, 22).

As shown in Fig. 1*A*, in a PVDI system, a PV 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. No batteries are used in the system: The pump only runs during the daytime, and energy storage is in the height of the column of water in the reservoir. Sizing of pumps, reservoirs, and fields is done on the basis of water availability and local evapotranspiration needs. The system passively self-regulates: Because 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. This is illustrated and described further in Fig. 1*B*.

To test the efficacy and impact of this concept, we monitored the installation and use of three 0.5 ha PVDI systems in the Kalalé district of Northern Benin (Fig. S1) beginning in November 2007. The PVDI systems were conceived, financed, and installed[*] by an NGO, the Solar Electric Light Fund (SELF: http://www.self.org), to boost vegetable production from

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[*] Installation includes training of local maintenance staff and support through the first several years of operation. More information about project context and implementation can be found in *SI Text*.

[1] To whom correspondence should be addressed. E-mail: burney@stanford.edu.

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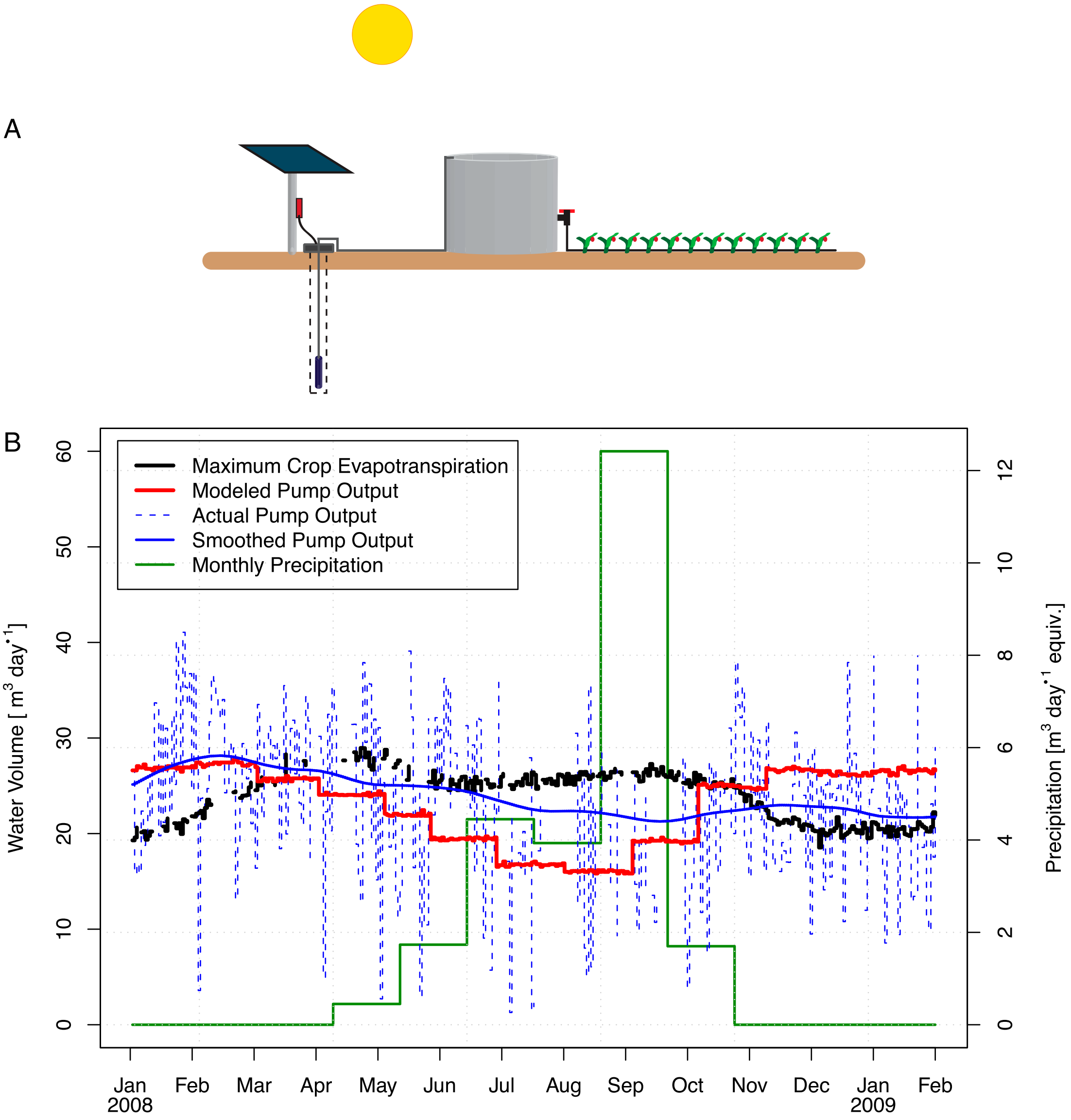

Fig. 1. (*A*) Cartoon schematic of a PVDI system. A PV array powers a water pump, which fills a large concrete reservoir; water is then gravity-distributed at a pressure of 1–3.5 m head through drip irrigation lines. (*B*) Passive regulation of PVDI systems shown for January 2008–January 2009. Maximum evapotranspiration (ET) need calculated from local weather data (assuming clear sky and no rainfall) is plotted in black. Any shortfalls for expected pump output for average annual weather patterns (*Red*) and actual pump output (*Blue*) are met by actual precipitation (*Green*).

communal gardens in an effort to combat high malnutrition and poverty levels typical of rural northern Benin and the Sudano–Sahel (23, 24).

In both treatment villages, PVDI systems were installed in conjunction with preexisting local women's agricultural groups. To test the technology with both surface and groundwater pumping systems, treatment villages were chosen on the basis of water source: In Village A, two identical side-by-side systems were installed with the two local women's agricultural groups; each draws water from a small year-round stream using a surface-mounted centrifugal pump. In Village B, the women's agricultural group uses a system that draws water from a 25 m borehole. Each PVDI system is used jointly by the 30–35 women in an agricultural group, each of whom farms her own 120 m^2 plot. The remaining plots are farmed collectively to fund group purchases and expenses.

Two "control" villages were chosen for matched-pair comparison with Villages A and B, based on similarity along several variables, including location along the same roads, administrative status, and size (25). Women's agricultural groups in the control villages grow vegetables in hand-watered plots, as had the groups in the treatment villages before intervention, allowing for comparison of the solar-powered drip irrigation systems to traditional methods. Household surveys were conducted in both treatment and control villages upon installation (in November 2007) and following 1 yr of garden operation (in November 2008).

In each village, all households represented in the women's groups were surveyed along with a randomly selected representative sample of households in the village, allowing for comparisons both within and between villages. From the household survey data, consumption aggregates were constructed according to Deaton and Zaidi (26). In treatment villages, production and sales were monitored for three randomly selected plots in each garden group (i.e., six from Village A, three from Village B). These data were assumed to be representative, and were used to calculate cost and payback time for the systems. Table S1 contains pertinent baseline data for village comparison, and additional information about survey methodology is contained in the methods section below.

Results

Food Security. Food security is typically subdivided into three components: (*i*) availability, or the existence of an adequate and stable supply of food; (*ii*) access, or the ability to obtain (physically or economically) appropriate and nutritious food; and (*iii*) utilization, or the ability to consume and benefit from nutritious foods (27). This definition provides an appropriate framework for evaluation of project impact.

Food Availability. The addition of 1.5 ha of irrigated land dedicated to vegetable production significantly altered local vegetable availability. Based on data from the women monitored in each agricultural group, each of the three PVDI systems supplied, on average, 1.9 tonnes of produce per month (including tomato, okra, pepper, hot pepper, eggplant, carrot, amaranth, moringa, and other greens). Household survey data reveals that during the first year of garden operation, use of the PVDI systems did not displace other agricultural production, as families with women in the women's groups continued to farm their other land as they had before, with corn, sorghum, yam, and cassava as the main food crops and some cash cropping of cotton and cashew.

During the first year of operation, the women farmers kept an average of 18% by weight (8.8 kg/month) of the produce grown with the PVDI systems for home consumption and sold the rest in local markets. The vegetables kept by the women's agricultural group families generally augmented total produce consumption, as opposed to simply displacing purchases (purchases did not decrease significantly as overall consumption rose). Garden products penetrated local markets significantly: Vegetable consumption increased during the rainy season (the time of greatest surplus for the women's group farmers) for the entire 4-village sample of households. This is discussed in greater detail below.

Food Access. Food access, both via home production and purchase, increased dramatically for the families of women's group farmers using the solar-powered drip irrigation technology. The coefficients of change for a variety of food access indicators (Y) were derived from baseline and follow-up household survey data using the fixed-effects model

$$Y \sim t + vt + wt + vwt$$

where t is a dummy variable indicating the time step (baseline survey or follow-up survey), v is a dummy variable indicating whether or not a particular household was in one of the treatment villages, and w is a dummy variable indicating whether or not a household had a member in one of the women's farming groups.

Fig. 2 provides the robust fixed-effects regression coefficients in the above model for a variety of food security indicators. Most notably, project households saw their total per capita daily consumption expenditure (CE) increase in comparison with other households (Fig. 2, *Upper Line*, *Red Points*), with the main component of this change being increased food CE (Fig. 2, *Second Line*, *Blue Points*)[†]. This increase in total CE represents a gain of >80% compared to the preimplementation village average baseline ($0.69 increase over $0.85). The food share of total CE increased significantly both across the sample as a whole and for project beneficiaries in comparison to the whole (Fig. 2, *Third Line*, *Blue Points*)—a result of higher cereal and pulse prices—though total CE increased only for project beneficiaries. The nonfood component of CE decreased significantly for the whole sample; in contrast, for project beneficiaries there was no significant change in nonfood CE.

As noted in Table S1, most households surveyed fell below the "dollar-a-day" CE poverty line of $1.25 [2005 purchasing power parity (PPP)] in 2007, with households slightly worse off in the treatment villages, and some variation across women's agricultural groups. Although reported incomes from a variety of sources increased across the entire sample in 2008, the percentage of nonproject households under the poverty line actually rose from 73% to 89% ($p = 0.001$), while the percentage of project households under the poverty line remained constant at 85%.

Looking more closely at changes in consumption patterns across commodity groups (Fig. 2) confirms that, as expected, consumption of vegetables for the women's group households increased significantly over the year compared to the rest of the sample. Breaking this down by season reveals that this trend was driven almost entirely by increased consumption during the dry season. As mentioned above, vegetable consumption increased across the entire sample during the rainy season.

The women's agricultural group members utilizing the PVDI systems became strong net producers in vegetables with extra income earned from sales, significantly increasing their purchases of staples, pulses, and protein during the dry season, and oil during the rainy season (Fig. 2). Finally, survey respondents were asked how frequently they were unable to meet their household food needs. Based on the frequency and most recent incident, households were assigned a food insecurity score ranging from zero (no problems during the previous year) to one (perpetually unable to meet food needs). This score changed significantly for project beneficiaries (Fig. 2, *Bottom Row*), as they were 17% less likely to feel chronically food-insecure. In short, the PVDI systems had a remarkable effect on both year-round and seasonal food access.

Food Utilization. In terms of food utilization, during the first year of the solar-powered drip irrigation project, vegetable intake across all villages increased during the rainy season by an amount equivalent to about 150 g per person per day (raw weight), or approximately one serving per day. For project beneficiaries, this amount was 500–750 g per person per day (raw weight), equivalent to 3–5 servings of vegetables per day (the USDA Recommended Daily Allowance for vegetables), and most of this change took place in the dry season. While it is not possible to directly quantify the health and nutrition status impacts of the PVDI systems, as no anthropometric measurements or biochemical tests were done as part of project impact assessment, previous studies indicate that changes in nutritional intake from vegetable gardens in the developing world can have significant impact on height-for-weight ratios and a variety of biochemical indicators due to their protein, vitamin, and mineral contributions to the diet (28). Over time, such projects may have larger impact, given that the World Bank estimates that 20–25% of the global disease burden for children is due to undernutrition (29).

The effect of additional produce availability in local markets did not result in significant changes in vegetable purchases for nonproject beneficiaries in treatment villages relative to control villages. This may be due to the fact that village markets are not isolated, and individuals routinely travel to other villages to make purchases. Other pathways of project health impact include increased ability to pay for health services and decreased disease burden due to improved nutritional status; however, families reported no significant increases in spending on health care, nor any significant reduction in self-reported incidence of malaria or diarrheal diseases.

Sustainability. In addition to measuring food security impacts, data from the first year of system operation may also be used to calculate initial estimates of project economic and environmental sustainability. Technical and social sustainability are addressed in *SI Text*.

[†] We use CE as a measure of welfare to account for household consumption of own agricultural production and the erratic nature of agricultural income.

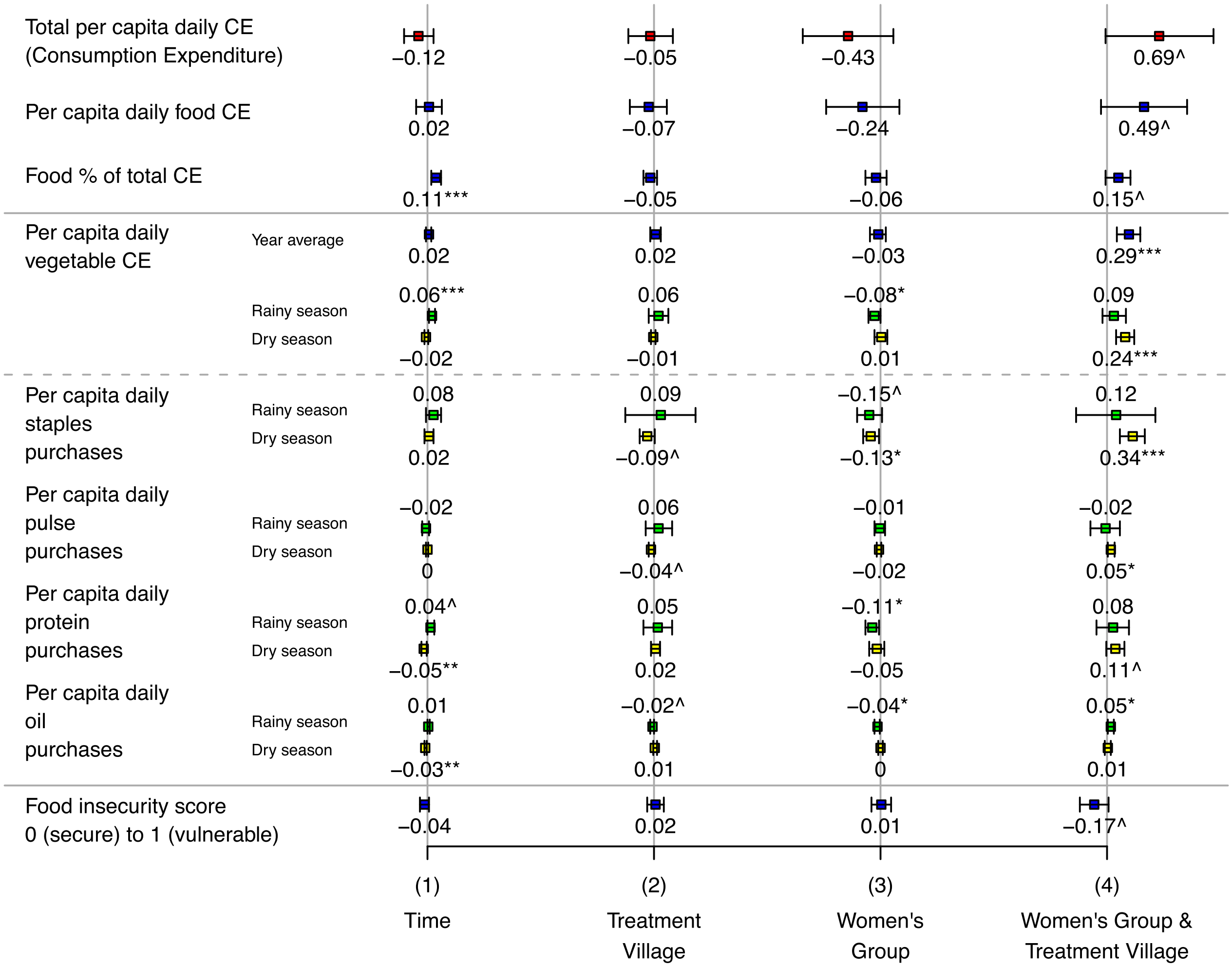

Fig. 2. Robust fixed effects regression coefficients for project impact on food security indicators. Column 1 shows the difference in outcome variables across all villages and households between November 2008 and 2007 (the overall time trend). Column 2 shows the effect difference for households in treatment villages versus households in control villages over time (the simple effect of living in a project village); column 3 shows effect difference for households with a member in a women's agricultural group versus non-group-member households across both treatment and control villages over time (the simple effect of being in a women's agricultural group). Finally, column 4 gives the difference-in-difference coefficient for project impact—the difference in each outcome variable between women's group member households in treatment villages and the rest of the sample—over the first year of the project. All consumption and purchase data account are given in per capita daily USD at purchasing power parity (PPP), accounting for inflation and allowing for comparison between metrics. Red and blue values are average values for the entire year; green and yellow markers show breakdown for rainy and dry seasons, respectively. [Error bars indicate 95% confidence range; significance: $^p < 0.1$ $*p < 0.05$ $**p < 0.01$ $***p < .001$]

Economic Sustainability. We compare the PVDI systems installed in northern Benin with a hypothetical alternative: An identical irrigation system in which a liquid-fuel (gasoline, diesel, kerosene) engine-driven pump has been substituted for the PV array and pump. For rural villages across the Sudano–Sahel, liquid-fuel pumps are the most likely alternatives to a PVDI system [and are commonly used in the region, as in (30)]: They are appealing due to their lower up-front costs, though fuel supplies may be unreliable and fuel prices volatile[‡]. Fig. 3 provides the investment analysis for a surface-mounted PVDI system and a very inexpensive liquid-fuel pump system, across different PV array and fuel prices (full model specifications are given in Table S2). Particularly when fuel prices are higher, PVDI is cost-competitive, even with the very high array prices associated with the pilot project. With lower array prices, as could reasonably be assumed for a

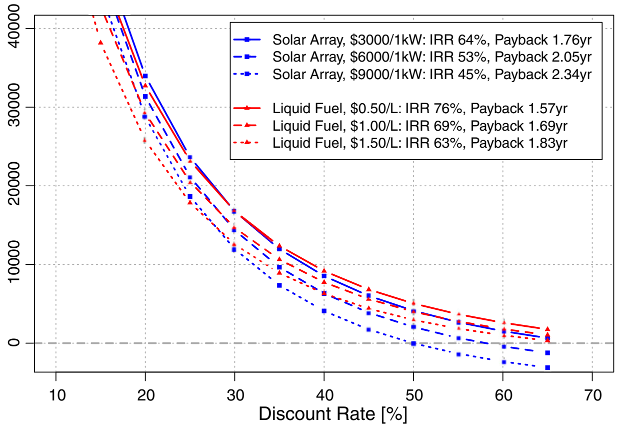

Fig. 3. NPV of comparable solar- and liquid-fuel-powered drip irrigation systems across discount rates for a range of photovoltaic system and fuel costs ($n = 15$ yr).

[‡] In the northern Benin case, both solar- and diesel-powered systems are preferable to human-powered pressure treadle pumps, which in many cases cannot provide enough lift, and require substantial human drudgery.

larger-scale project, PVDI is a cost-effective intervention in areas like northern Benin.

Due to the higher up-front costs of a PVDI system (versus a liquid-fuel pump-based system), it is likely a realistic investment only for groups of extremely poor farmers. While group-based systems may suffer from free-riding, they also provide mechanisms for risk-spreading, access to capital (through group-based loans), economization of input purchases and marketing expenses, the ability to negotiate land and water rights, and knowledge-sharing. Whereas individual-based drip irrigation programs often report high rates of disadoption [e.g., (17)], group-based PVDI systems may provide the stability and institutional support necessary for the extremely poor to invest in production of high-value crops.

The PVDI system can be understood to place an upper limit on the up-front costs of distributed pumping and irrigation technologies, with top-of-the-line long-lifetime components and deep water pumping ability integrated into a full management and training package. That such a system not only has a strong and significant impact, but is cost competitive and desirable locally, indicates that there could exist a large market for this type of product. With an improved local supply chain, transportation costs associated with maintenance could be driven down, and system cost could be driven down by using lower-quality, shorter-lifetime components. PVDI systems could ultimately take on many different forms, including much lower-cost, shorter-lifetime technologies sold privately to individuals.

Environmental Sustainability. The environmental sustainability of any PVDI system depends upon proper adaptation of the basic design to local conditions. At the village or subvillage level, individual systems may be constrained by water resources: Surface water PVDI systems must be designed only for year-round seasonal sources with adequate flow during the dry season; groundwater PVDI systems must be designed based on existing groundwater resources (either previously drilled boreholes or new ones based on hydrogeological surveys). Beyond these very local constraints, however, national and regional level estimates suggest that irrigation can sustainably play a much larger role in agriculture in Benin and the Sudano–Sahel: Benin currently uses only 1.3% of its internal renewable water resources (IRWR), and the entire Sudano–Sahel uses 35% of its IRWR (12). Although the renewable water resources of the Sudano–Sahel are not at present fully exploited, using this resource efficiently is critical, especially under projected population growth and climate change. Microirrigation technologies will therefore likely play an important role in more efficiently—and thus more sustainably—expanding agricultural water access in the Sudano–Sahel.

When considering the energy requirements for expanded irrigation in rural Africa, PVDI systems have an additional advantage over liquid-fuel-based systems in that they provide emissions-free pumping power. Assuming that a similar size pump set (0.75–1.5 kW) would replace the solar-powered pump and would require 0.15 L of fuel per cubic meter of water pumped, we calculate that each garden avoids a minimum of 0.86 t of carbon emissions per yr (12.9 t over a 15 yr lifetime) in comparison with the liquid-fuel alternative.

Discussion

Irrigation—and in particular, drip irrigation—is often cited as an appropriate technology that can promote food security and economic development in sub-Saharan Africa; this study quantifies the local impacts of PVDI technology in the rural Sudano–Sahel. Globally, rising food and oil prices are estimated to have pushed at least 100 million additional people into poverty in 2008 (31, 32). Against this backdrop, and compared to control households, users of the PVDI systems fared relatively well: Their standard of living increased relative to nonbeneficiaries (by 80% of the baseline), their consumption of vegetables increased to the Recommended Daily Allowance, and the income generated by production of market vegetables enabled them to purchase staples and protein during the dry season. Overall, this study thus indicates that solar-powered drip irrigation can provide substantial economic, nutritional, and environmental benefits to populations in the Sudano–Sahel.

When considering the requirements for implementing a large-scale PVDI project, it is important to recognize that the PVDI system in this study is not an off-the-shelf product, but rather an integrated technology and management package with a significant associated learning curve. Access to extension services and technical support will be critical to ensuring the sustainability and long-term functionality of individual PVDI systems. Furthermore, widespread uptake of PVDI technology will require regional manufacture and a local supply chain, linkages to larger markets, and the financial institutions necessary for a vibrant private market in which consumers can reasonably invest in PVDI systems. While these institutional supports are developed, long-term involvement by PVDI project implementers will be critical in financing PVDI systems, facilitating extension services and maintenance, coordinating market access among groups of PVDI users, and providing the stability of demand necessary to jump-start the private sector. With the proper support, successful widespread adoption of PVDI systems could be an important source of poverty alleviation and food security in the marginal environments common to sub-Saharan Africa.

Methods

Photovoltaic Pump Performance Calculations. To calculate crop evapotranspiration needs, we follow Food and Agriculture Organization (FAO) of the United Nations Guidelines (33) and use regional weather data from the National Climatic Data Center's Surface Global Summary of the Day database (34). To calculate expected pump performance we follow Narvarte (35)

$$Q = \int \frac{P_{\mathrm{nom}}(G/G_{\mathrm{ref}})n_A n_{MP}}{2.725 H_T} dt$$

where Q is total pump output, P_{nom} is the nominal array power (here 780 W for the surface pump systems), G is the on-plane solar irradiance, G_{ref} is the irradiance at standard test conditions, n_A is the array efficiency (including temperature effects), n_{MP} is the efficiency of the pump, and H_T is the total dynamic head (here we use specs from the surface pump systems: 6 m static head, a maximum pumping speed of 120 L/min, and 63 mm pipe, giving a maximum total dynamic head of 7.42 m). We use monthly regional irradiance data from the European Commission's Photovoltaic Geographical Information System database (36), and use the actual daily running time of the pumps as reported by local support staff.

Research Design and Data. In 2007, household surveys were conducted for each woman in the women's agricultural groups and for a random representative sample of 30 households in each village (stratified by census zone), with females over 18 as respondents. Surveys were conducted following installation of the PVDI systems but before any harvest. Any women who were away from the district at the time of the survey were omitted.

In 2008, enumerators repeated surveys with each woman in the agricultural groups who had been interviewed the year before, if possible. For the village sample, enumerators returned to the previously sampled households and interviewed the same respondent, wherever possible. If an original respondent was not present and another woman over 18 years old in the household could answer the questions, she was interviewed and this was noted. If a respondent's household could not be refound, a neighboring household was substituted and this was noted.

Along with basic demographic and socio-economic questions, the household surveys conducted in November 2007 and 2008 contained detailed agricultural production tables, rainy and dry season food purchase and consumption tables, nonfood purchases and assets tables, and detailed questions on income, health, and access to services.

To monitor yields and sales percentages, three women were chosen at random from each women's agricultural group. With the help of local support staff, these women recorded their individual harvest information: Product harvested, weight, amount kept, amount sold, and sale price. These data were assumed to be representative within an agricultural group, and used for the economic analysis of the PVDI systems.

Construction of Consumption Aggregates and Food Security Indicators. We constructed the CE aggregate from the household survey data according to the methodology described in Deaton and Zaidi (26). We converted household values to per capita daily values by dividing by household size. Finally, to present CE values in dollar amounts at PPP, we used 2005 values from the World Bank International Comparison Project (37), and adjusted prices and poverty lines for inflation using 2007 and 2008 Consumer Price Index data from the International Monetary Fund's World Economic Outlook database (38).

Economic Analysis and Technology Comparison. As shown in Table S2, a 0.5 ha solar-powered drip irrigation system (surface pump) costs approximately \$18,000 to install, or \$475 per 120 m^2 plot, and requires annual expenses of \$5,750 (\$143.75 per plot) in inputs, labor, and support of technicians and extension services provided by regional agricultural organizations. The system uses high-quality, long-lifetime pressure-regulated drip irrigation lines as opposed to cheaper, shorter-lifetime alternatives. Using modest estimates for total revenues of \$10,000 in the first year and \$16,000 per year thereafter (derived from the sales data for the three women monitored from each agricultural group), such a system has a payback time of approximately 2.3 yr. We also consider two additional PVDI scenarios: (*i*) one in which the array and installation cost \$4,500, which would be reasonable for installation of 6–10 systems, whereby fixed costs could be spread over a greater number of systems; and (*ii*) one in which the array and installation cost \$3000, which would be reasonable for a future large-scale installation with a drop in PV array prices.

For the liquid-fuel pump comparison, we assume a small engine-driven pump set replaces the photovoltaic array and pump in the PVDI system. A wide variety of such gasoline, diesel, and kerosene pumps exists, with varying lifetimes and fuel efficiencies. We compare to the most inexpensive option: A relatively small (0.75–1.5 kW) system with a start-up cost of \$1000 (for pump and pipes that will last 5 yr) and \$100 per year for maintenance. Apart from the pump, the system remains the same: We assume that forty 120 m^2 plots are connected to the same large reservoir and high-quality irrigation lines, and that the same amount of water is pumped over the course of the year (average of 25 m^3 per day). We use an average value of 0.15 L of fuel per cubic meter of water pumped, and investigate a range of fuel prices, from \$0.50 to \$1.50 per liter (\$1/L was the approximate average price in the district during 2008). We assume that fuel is readily available.

The net present value (NPV) and internal rate of return as shown in Fig. 3 are calculated over a 15 yr time span (the assumed lifetime of the solar panels). While the lifetime of solar panels in the developed world may be higher (approximately 25 yr), many technologies in the developing world suffer from unexpectedly short lifetimes; we therefore use a conservative estimate of 15 yr in our analysis.

To calculate the carbon emissions avoided by using a PVDI system in lieu of a liquid-fuel pump, we use 2006 Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme guidelines (39). We assume that gasoline has an energy content of 44.3 TJ/Gg, a carbon content of 18.9 kg/GJ, specific density of 0.75 kg/L.

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