AGREKON

Vol 40 Number/Nommer 2
June/Junie 2001

Published by the
Agricultural Economics
Association of South Africa

Gepubliseer deur die
Landbou-ekonomievereniging
van Suid-Afrika

FIRST-ORDER ECONOMIZING: IRRIGATION TECHNOLOGY ADOPTION AND THE FARM

P.N. Wilson[1]

Expected future water shortages and emerging environmental concerns place micro-irrigation near the forefront of technological alternatives for the agricultural sector. Drip irrigation--under favorable soil, biological, climatic, organizational, and economic conditions – is economically preferred to traditional flood, furrow, and even sprinkler technologies. However, superior management is required to produce the incremental yield increases necessary for acceptable returns on this investment. Other incremental benefits from adopting drip technology are realized through complementarities between the technology, other inputs, and the firm's marketing strategy.

1. INTRODUCTION

The human community is physically and socially dependent upon fresh water. Individual life requires drinking water and water for food production. Our communal life, in addition to our individual needs, demands an adequate quantity, safe quality, and efficient allocation and distribution of existing water supplies. From the beginning of recorded human civilization, societies go to war and/or cease to exist when these water demands are not met (Gleick, 1998 and Postel, 1999).

Water analysts in the last decade of the 20th century have produced a series of reports on the impending fresh water crises in many areas of the world (Anderson 1995, Simon 1998). In some arid regions, groundwater is being mined on an unsustainable basis (e.g. China, India, Mexico City, and some areas in the Western U.S.). More generally, water consumption has increased beyond the increase attributable to population growth. For example, since 1900 the U.S. population has doubled, but over the same time period growth in per capita water consumption has exceeded 500 percent. This demand pressure on existing water supplies creates political pressure on government to force conservation, develop new local supplies, and/or import water from other regions.

[1] *Department of Agricultural and Resource Economics, P.O. Box 210023, The University of Arizona, Tucson, Arizona 85721-0023, Tel +1 520 621 6258; fax +1 520 621 6250; e-mail pwilson@ag.arizona.edu.*

Quantity is not the only challenge. The quality component of the water scarcity equation is more alarming. Clarke (1993) notes that half the world's population suffers from infections that are waterborne: yellow fever, malaria, and river blindness. Water-related diseases affect 250 million people annually and 5 to 10 million of these people die from these diseases (Nash 1993). Four out of five child deaths in developing countries are attributed to waterborne diseases (Jayal 1985). In the agricultural sector, poor quality irrigation water and unsustainable irrigation practices have reduced the productivity of an important percentage of agricultural lands in the United States (23%), Pakistan (26%), Egypt (33%), Uzbekistan (60%) and Turkmenistan (80%). Yet most analysts agree that in the aggregate, the earth has enough water to sustain humanity's future. Our challenge in the 21st century is matching the quantity and quality of water supplies to their highest net value uses within reasonable political constraints.

Water-conserving irrigation technologies are widely regarded as one very important tool for easing the future shortage of fresh water supplies in some regions of the world. By substituting capital and management expertise for water while increasing output per cm^3, existing water supplies can be conserved with no adverse economic impact. These water-conserving technologies range on a capital/management continuum from management intensive weather reporting and irrigation scheduling services to micro-irrigation systems that are both capital and management intensive. Frequent claims that these technologies reduce water use by up to 40%, while simultaneously increasing output per hectare, produce hope that improved water management practices and technologies will alleviate future fresh water shortages.

The next section of this paper defines first-order economizing for irrigation technology adoption decisions and contrasts this concept with day-to-day economic decision-making associated with water management. Two standard adoption models are discussed. A discussion of economic feasibility lessons learned is the third section. I discuss the irrigation technologies analyzed in recent years, particularly drip irrigation, and review the results of these economic analyses. A critical evaluation of previous work, including my own, concludes this section of the paper. A discussion of the economics of complementarities applied to drip irrigation follows. The paper concludes with an emphasis on two key considerations associated with the economic feasibility of drip irrigation.

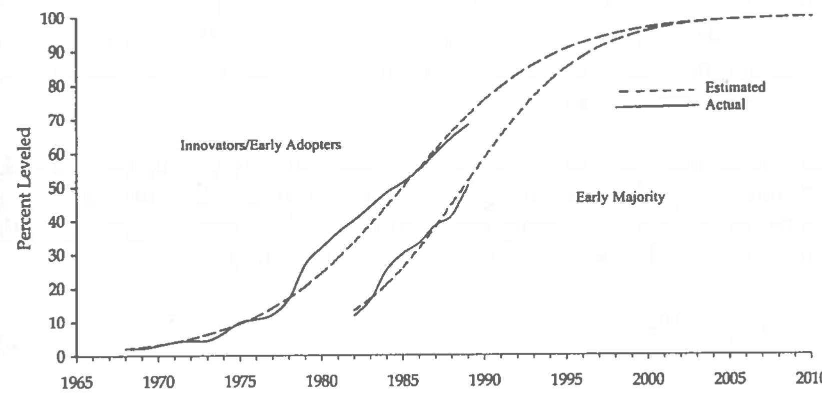
2. FIRST-ORDER ECONOMIZING

A key decision in business startups is the choice of technology. The technology selected is a critical determinant of the cost structure of the business. Likewise, the opportunity set of activities associated with marketing and distribution are influenced by the production possibilities set. First-order economizing is the economic decision to adopt a particular technology given the market strategy of the business. In contrast, second-order economizing is associated with the day-to-day operational decisions within the constraint of the technological opportunity set. First-order economizing also characterizes the decision to change technologies, generally to a lower-cost, productivity enhancing technology.

In the case of many long-term technologies, like irrigation systems, the farmer faces a decision that is costly to reverse and requires planning. First-order decisions entail an analysis of both variable and fixed costs over time. In addition, the investment will require equity and/or debt financing. The decision to go forward with an significantly irreversible irrigation investment requires a high net present value that reflects the opportunity cost to the firm of keeping its investment options open (Pindyck, 1988).

The adoption and diffusion literature has isolated key factors in the first-order economizing decision (Feder *et al,* 1985). Expected profitability is an important driver for the adoption decision. Adoption also is a function of the quality and quantity of information available to the farmer and is dependent on first-hand experience with the technology. Adopters are generally better educated, have higher social participation rates, farm larger land areas, and have higher incomes than nonadopters. Risk preferences, government policies (e.g., subsidies, taxes, extension programs), and the costs of acquiring information about the new technology are important decision variables as well. This multi-dimensional adoption decision generally produces an S-shaped logistic curve that represents the diffusion process associated with the technology. For example, Figure 1 illustrates aggregate adoption of level field and basin technology in central Arizona for innovators and early majority farmers.

A wide variety of conceptual and empirical models have been used to capture the important parameters in the adoption process. Consider the decision-making environment of a farmer that can be approximated by a mean-variance model (Anderson *et al,* 1999). While difficult to estimate empirically, this framework captures the decision-making environment and provides a guide for developing empirical models. Suppose the new, water-conserving



Source: Anderson, Wilson, and Thompson 1999

Figure 1: Examples of S-shaped diffusion curves for level fields and basins in Central Arizona, USA

technology and the conventional system are represented by scale neutral per hectare production functions $f(w_f)$ and $g(w_g)$ respectively, where $f', g' > 0$, $f'', g'' < 0$ and w is water applied per hectare. For simplicity assume the grower produces only one crop (y) which is sold at price *p*, where the yield per hectare associated with the conventional technology (g) is known but where $y_f = f(w_f) + \epsilon$ and $\epsilon \sim N(0, \sigma_\epsilon^2)$. The decision-maker must allocate the two technologies within the total irrigated area, $\bar{L}$. Finally, assume that the decision-maker overestimates σ_ϵ^2 by $(1+\theta)$ due to inadequate information (i.e., an increasing, θ where $\theta > 0$) and/or a personal hesitance to adopt new production practices.

The resulting certainty equivalent, mean-variance model can be written as:

$$\max_{w,L} \; p_{ce} = p\left[Lf(w_f) + (\bar{L} - L)g(w_g)\right] - p_L L - p_w\left[Lw_f = (\bar{L} - L)w_g\right] - \frac{\lambda}{2}p^2L^2(1+\theta)\sigma_e^2 \quad (1)$$

where L is the land area allocated to the new technology at price p_L and p_w is price of water. The Arrow-Pratt risk aversion coefficient, λ ,which is assumed to be greater than zero, demonstrates decreasing absolute risk aversion, $\partial\lambda / \partial\pi_{ce} < 0$, and contains the arguments of all the parameters which locate the EV frontier, in this case, $\lambda = \lambda(p, p_w, p_L, \bar{L}, \sigma_\epsilon^2)$. The first-order conditions for optimal water use equate the land-weighted returns above variable costs for the two technologies, $L(pf - p_w) = [\bar{L} - L](pg' - p_w)$. The nature of the production functions guarantee the second-order conditions for exogenously determined output prices.

The farmer must optimally allocate the fixed resource, $\bar{L}$ between a risky technology (e.g. drip irrigation) and a comparatively safe alternative (e.g. furrow irrigation). By taking the derivative of (1) with respect to L, the optimal acreage devoted to the new, water-conserving technology is:

$$L^* = \frac{p[f(w_f) - g(w_g)] - p_L + p_w(w_g - w_f)}{\lambda p^2 (1+\theta)\sigma_\epsilon^2} \; for\; 0 \le L \le \bar{L} \qquad (2)$$

The quadratic nature of the risk factor in equation (1) guarantees that L^* is an optimal value. The numerator in (2) reflects the importance of the difference in expected per hectare yield, the per hectare investment cost of the new technology and the per hectare value of the water savings. As we shall see in the next section these relative profitability factors are critical components for the adoption or non-adoption of water-conserving technologies. The denominator of this optimal condition argues for the consideration of risk preferences, information, and variability associated with the new technology as important considerations. Further examination of (2) yields the following ceteris paribus assertions: the impact of p and p_w on L^* is uncertain, $dL^*/dp, dL^* dp_w \gtrless 0$; hectares devoted to the new technology will increase with a decline in the investment cost associated with the water-conserving system ($dL^*/dp_L < 0$); and better information and a reduction in variability encourage the adoption of water-conserving irrigation technologies ($dL^*/d\theta, dL^*/d\sigma_\epsilon^2 < 0$). In a non-ceteris paribus world, these economic relationships interact to facilitate, or constrain, the diffusion of the technology.

The second adoption model is a financial investment framework that is an operational decision tool for agribusiness managers. This empirical model analyzes the after-tax profitability of the decision to change irrigation technologies (Wilson *et al*, 1984). Investment tax credit, principal and interest payments or lease finance payments, depreciation, and a marginal tax rate are incorporated into the model to generate after-tax revenues and costs. Other tax implications, such as those for soil and water conservation tax credits, if they exist, can be included. Revenue and cost information from enterprise budgets are used in the investment model. For a given crop:

$$R = (H)(P)(Y) \qquad (3)$$

$$C = H(L+E+T+F+H+M+O) \qquad (4)$$

where:

R = returns,
C = operating costs,
H = number of hectares,
P = price of the harvested crop,
Y = yield,
L = labor/management costs,
E = energy costs,
T = tillage costs,
F = fertilizer costs,
H = herbicide costs,
M = maintenance and repair costs, and
O = other costs (such as insecticide expenditures).

Let j be the new technology and k the existing technology. A measure of annual (t) net returns before taxes NR_t^B, incremental to the investment, can be calculated as:

$$NR_t^B = (R-C)_{jt} - (R-C)_{kt} \qquad (5)$$

For simplicity, assume that the crop is the same over the entire planning horizon, n. The net present value of the investment on the after-tax basis is:

$$NPV_t^A = \sum_{t=0}^{n}\left[NR_t^B - MTR\left(NR_t^B - D - I_t\right) - IC_t - LP_t - DP\right](1+i)^{-t} \qquad (6)$$

where

NPV_t^A = net present value, after taxes, over the n year planning horizon,
MTR = marginal tax rate (state and federal),
D = depreciation for tax purposes,
I = interest paid on irrigation investment,
IC = investment tax credit claimed,
DP = downpayment,
LP = loan payment of principal and interest,
T = year (0 to n), and,
I = opportunity cost of capital.

Equation 6 can be solved for the net present value of the investment, or letting $NR_n^A = 0$, the internal rate of return of the irrigation investment is found by solving for i. Key parameters in this model can be varied to obtain breakeven prices, yields, energy costs, etc. As discussed earlier, different types of financing considerations (e.g. leasing) can also be incorporated into the model.

Other methods for evaluating the economic feasibility of water-conserving irrigation technologies include stochastic dominance (Harris & Mapp, 1986) and econometrics (Caswell & Zilberman, 1985 and Shaw *et al*, 1995). An evaluation and critique of several of these analyses, particularly those dealing with the drip irrigation adoption decision, is the focus of the following section.

3. ECONOMIC FEASIBILITY LESSONS LEARNED

Drip irrigation is a very "old" irrigation technology. Nebuchadnezzar used a drip system to irrigate the Hanging Gardens of Babylon 2,600 years ago. Yet the use of drip technology on commercial farms is relatively new, starting in the 1960's in Israel and expanding rapidly to other areas of the world. Today micro-irrigation, with drip technology the largest component, accounts for approximately 50% of the irrigated land in Israel, 71% in Cyprus, 21% in Jordan, 9% in South Africa, and 3% in the United States (Table 1).

Drip irrigation also is the technology of choice in the 200 000 hectares of plastic greenhouses in the world (Jensen & Malter, 1995). This form of protected agriculture represents a rapidly increasing source of higher value crops (e.g. flowers, tomatoes) throughout the world.

Drip irrigation often is labeled a water-conserving irrigation technology. Reports of water savings of 10-30% are not uncommon. Likewise, this system of pumps, filter stations, fertilizer injection pumps, PVC mains, and above ground or below ground distribution tubes is regarded as a land-augmenting technology. Its adoption on coarse-textured or sandy soils increases the productivity of those fields. Therefore, the profit incentive for choosing this technology for a new enterprise, or substituting drip irrigation for a more traditional system (e.g. furrow or flood) is largely explained by lower water costs and higher yields.

The evaluation of the economic feasibility of water-conserving irrigation technologies has a long and on-going tradition in the arid West of the United States. Over the last two decades, analyses have been completed on micro-sprinklers (Wilson, et. al 1976), laser leveling (Daubert & Ayer, 1982 and

Table 1: Use of micro-irrigation, leading countries and world, 1991[1]

Country	Area Under Micro-irrigation (hectares)	Share of Total Irrigated Area Under Micro-irrigation[2] (percent)
United States	606,000	3.0
Spain	160,000	4.8
Australia	147,000	7.8
Israel[3]	104,302	48.7
South Africa	102,250	9.0
Egypt	68,450	2.6
Mexico	60,600	1.2
France	50,953	4.8
Thailand	41,150	1.0
Colombia	29,500	5.7
Cyprus	25,000	71.4
Portugal	23,565	3.7
Italy	21,700	0.7
Brazil	20,150	0.7
China	19,000	<0.1
India	17,000	<0.1
Jordan	12,000	21.1
Taiwan	10,005	2.4
Morocco	9,766	0.8
Chile	8,830	0.7
Other	39,397	—
World[4]	1,576,618	0.7

[1] *Micro-irrigation includes primarily drip (surface and subsurface) methods and micro-sprinklers.*
[2] *Irrigated areas are for 1989, the latest available.*
[3] *Israel's drip and total irrigated area are down 18 and 15 percent, respectively, from 1986, reflecting water allocation cutbacks due to drought.*
[4] *13,820 hectares (11,200 of them in the Soviet Union) were reported in 1981 by countries that did not report at all in 1991; world total does not include this area.*
Source: *Postel 1997:105*

Anderson *et al*, 1999), drip irrigation (Wilson *et al*, 1984), linear move/LEPA (Wilson *et al*, 1986), water harvesting (Coupal, 1985) and surge flow (Coupal & Wilson, 1990). The following research case studies represent four examples of efforts to develop an understanding of the economic feasibility and adoption decisions associated with drip irrigation. These four papers are not exhaustive of the literature but they capture a shared understanding of the opportunities and challenges of drip irrigation on commercial farms.

3.1 Central Arizona, USA

In the early 1980s, Wilson, Ayer and Snider completed possibly the first comprehensive economic feasibility analysis of drip irrigation. Local interest in this technology was stimulated by expectations of increasing water costs in the near future due to deeper pumping lifts, higher energy prices, and escalating surface water prices. The adoption of drip irrigation technology was perceived by Arizona cotton growers as an economically viable response to higher water costs. At the time, both surface and subsurface systems were considered although experiences over the last twenty years have tipped the economic scales in favor of buried drip tubes. The second model discussed in the previous section was used in this economic feasibility analysis. All data were obtained from interviews with cotton growers and equipment suppliers.

In 1983 US dollars, drip irrigation investments of US$1,976-3,458 per hectare implied "buying my land again". This significant investment was financed through operating lines of credit, financial reserves, and equipment supplier loans or leases. Acreage initially was converted from furrow to drip irrigation in small 8-24 hectare blocks depending on the grower's learning curve and financial resources. Several efforts to jump from 24 hectare test plots to full-scale 2,500 hectare adoption levels in one or two years failed. Subsurface drip experienced lower operating costs than either furrow or above ground drip, and with an assumed yield increase of 539 kgs/h and a US$2,470/h investment, subsurface drip was the economically preferred irrigation technology.

A distinguishing feature of the Arizona feasibility study was sensitivity analysis on key decision variables. Cotton prices below US$1.32/kg produced negative net present values at a 12% discount rate. At US$1.32/kg, the sub-surface drip system was profitable with a yield increase over the furrow system of at least 164 kg/h and a low investment cost of <US$2,470/h. This analysis demonstrated that a substantial yield increase over the traditional technology and a favorable commodity price were necessary and sufficient conditions for favorable adoption. As expected, as water prices increased, the profitability of both drip systems improved relative to the furrow system.

A second contribution of the Wilson, Ayer and Snider study was the evaluation of learning curves and their impact on profitability. Feasibility studies often assume optimal yield increases in year one of the project. This

unrealistic expectation biases the analysis in favor of the new technology. Growers consistently noted to the authors that their learning curves with drip technology were at least three years, where no yield increase was experienced in the first year and gradual improvements in yield were realized thereafter. The Arizona study demonstrated that realistic learning curves produced positive net present values for only lower-cost system investments. In contrast, the grower who was a "quick learner" could improve the relative profitability of the drip system dramatically.

3.2 Central valley of California, USA

Similar concerns about increasing water costs, and in the case of California, water shortages led Caswell and Zilberman (1985) to evaluate the adoption of water-conserving technologies by grape, deciduous tree fruit, and nut growers. The authors were interested in the factors that explained adoption patterns of furrow, sprinkler, and drip irrigation systems. Primary data were obtained from farm advisors, not growers, in six counties. Farm management data were obtained from secondary sources. A multinomial logit model was used to estimate the adoption probabilities.

One of Caswell and Zilberman's important findings was that growers pumping groundwater were more likely to adopt water conserving irrigation technologies. Most land-augmenting irrigation systems require pressurization. Yet many irrigation districts are designed and operated for furrow or flood irrigation. Water delivery in these districts is not pressurized and water is not always available to the grower on a timely basis. Therefore, the availability of ground water irrigation pumps was a statistically significant variable in predicting adoption.

The authors discovered that location matters in adoption decisions. Growers in Kern County were more likely to adopt sprinkler and drip irrigation than growers in the other counties. Why? First, Kern County has relatively higher water costs. Secondly, the soils in Kern County are sandier or lighter than soils found in the other counties. And finally, Kern County enjoyed a stronger marketing network for water-conserving technologies and more shared experience among the growers. In contrast, growers in Kings County traditionally grew more row crops on heavier soils and faced relatively lower water costs. As a result, Kings County growers were less likely to adopt drip technologies. Traditional cropping patterns were also an important factor in the adoption decision. Almond and pistachio growers were more likely to adopt drip technology than walnut growers due to the deeper and more extensive root system of walnut trees.

Although the Caswell and Zilberman study was not an economic feasibility analysis, they did estimate gains in net revenue from adopting drip technology. King County growers lost US$63/h with adoption compared to their counterparts in four other counties. Farmers in Kern County gained US$128/h relative to the same four counties with their decision to adopt drip systems. Almond and pistachio growers in the Central Valley (all counties) gained US$165/h relative to grape and deciduous fruit farmers. And finally, growers with their own ground water irrigation systems gained US$165/h relative to growers in surface water irrigation districts.

3.3 Israel

Israeli agriculture has been the leader in the use of drip irrigation. An example of Israeli economic studies of irrigation technologies is Feinerman and Yaron's (1990) study of drip irrigation on kibbutz cotton farms (also see Fishelson & Rymon 1986). The authors were interested in estimating and explaining the parameters that promote the decision to adopt drip technology and the rate or speed of diffusion. Sprinkler and drip technologies were compared with drip being the "new" technology.

Thirty-eight growers were interviewed in this study. The authors found that yields per hectare were 10% higher under drip (4944 kg versus 4479 kg). Yield per cubic meter of water was 2.5% higher with drip when compared to sprinkler (1.195 kg versus 1.166 kg). These descriptive results supported, according to the authors, their claim that new technologies offer the opportunity to increase profitability. Statistical results from their logit model provided empirical support for the claim that increased profitability was the most important economic driver in the adoption decision.

Feinerman and Yaron gleaned two other important insights from their interaction with the growers and the data. First, they found that drip technology was most preferred when developing new cotton fields. The economic decision was more uncertain when switching from an established sprinkler system to a new drip design. Secondly, the authors found that learning curves were important in the adoption and diffusion process. Successful learning-by-doing (e.g. early profitability) accelerated the intra- and inter-farm diffusion of the technology.

3.4 Hawaii, USA

The adoption decision in this case study is between furrow and drip technologies on sugarcane fields. Shrestha and Gopalakrishnan (1993) argued strongly that although relatively profitability was a dominant parameter in the adoption decision, factors like irrigation efficiency, capital and equipment costs, land quality, and water quality were also important determinants. The authors used panel data from four plantations gathered over the period 1975-86. A total sample of 450 field observations were analyzed using a probit model.

The authors found that drip technology increased the productivity of fertilizer applications. In addition, water savings of approximately 12% were economically significant in their model for predicting adoption. Increased yields were a significant explanatory variable while the model also pointed out the importance of a short learning curve to induce adoption. Finally, this study substantiated the earlier finding that the productivity of lower quality soils increases relatively more under drip irrigation than heavier soils. However, the authors discovered that sugarcane yields also increased on fine-textured, soils with drip technology.

So under what conditions is the adoption of drip technology economically feasible? The reviewed literature agrees on several key factors. First, there must be a significant yield increase attributable to the new technology, ceterus paribus. Depending on the crop, this increase may range from 10-30% to justify the investment. Secondly, water savings reduce operating costs, particularly in high cost water areas and on sandier soils. However, water cost savings alone do not pay for the drip irrigation investment. Finally, the adoption of drip irrigation will most likely occur on coarser-textured soils, on new, start-up farms, and in areas where there is a demonstration effect—where technical information is widely shared and continuing education is available for the grower.

Only the Arizona study directly evaluated the economic feasibility of the drip irrigation investment decision. Net present value estimates for a 30 hectare field under realistic assumptions at the time ranged from US$ -399 to US$ 414 depending on the assumptions. This analysis pointed out the adverse impact of negative cash flows due to extended learning periods. Also, this economic evaluation clearly illustrated the importance of decision-maker preferences towards present and future dollars. Discount rates of 15-20% lowered net present value estimates to an indifference threshold between the adoption or non-adoption decision.

Regrettably, the human or management parameter in the decision process was absent in all the reviewed studies. Yield increases were generally assumed due to the mere existence of the drip technology. This attribution is only partially accurate. Drip irrigation is an example of intensive agriculture—production systems that demand daily supervision and monitoring by trained managers. Experience in Arizona has shown that drip technology operated with a furrow irrigation mentality is a recipe for economic failure. But when new irrigation technology is combined with a progressive management, the technical and economic complementarities transform the farm into a modern, sustainable agribusiness operation.

4. THE ECONOMICS OF COMPLEMENTARITIES

In the conventional production economics framework, technical complementarity implies that the marginal productivity of one input increases with an increase in the amount used of another input. Assume $y = f(x_1,x_2)$ where y is output, $f(\cdot)$ is a twice-differentiable quasi-concave production function, and x_1 and x_2 are production inputs. Technical complementarity between x_1 and x_2 exists if $\partial y/\partial x_1 \partial x_2 > 0$. Complementarity implies input interdependence that can lead to reduced costs. Complementarity has received only limited treatment as a factor creating competitive advantage for the firm.

Drip irrigation technology creates potentially significant input complementarities. Case study evidence indicates that the marginal productivities of labor, fertilizer, water, and machinery increase by adding drip technology to the production process. Automated irrigation systems substitute for irrigation labor and raise the productivity of the remaining water management personnel. Fertilizer usage declines under the drip system but yields increase thereby increasing the productivity of the marginal kg of fertilizer. Reduced water applications and higher yields produce higher productivity per cm^3 of water. And fewer cultivation passes over the field with subsurface drip systems reduces soil compaction and decreases machinery investment and operating costs. These input complementarities have been treated lightly or ignored in the reviewed literature.

Another interdependency often ignored in the technological adoption literature is the critical role of management in determining the relative profitability of an intensive agricultural technology. Our experience in Arizona, albeit somewhat anecdotal, indicates that economic gains to drip technology compared to furrow irrigation only occur under intensive water management. I define intensive management as the daily utilization of

science-based, modern management techniques to operate, monitor, and evaluate irrigation practices. Figure 2 illustrates this profitability pattern over increasing levels of management intensity. If we assume that a grower utilizes lower intensity management with a furrow irrigation system, then the adoption of a drip system will fail unless the grower makes major changes in water management practices. The economic success of the drip system is interdependent with the management input.

Milgrom and Roberts (1990) argued that not only do these complementarities exist between inputs but between business activities as well (e.g. production and marketing). Using the mathematics of complementarities, the authors prove that complementarities between activities due to technological adoption can create competitive advantages for the firm. To exploit these productive relationships requires coordination between traditionally separate business activities like procurement, production, and marketing. The full economic benefits from the technology only are achieved after a significant redesign of how the business is operated.

The implication for drip irrigation is vitally important for agriculturalists. When only production complementarities are included in economic feasibility studies, the decision to adopt drip technology is fraught with financial uncertainty due to high investment costs. But when marketing complementary are included in the feasibility models, that is, the ability to produce a higher quality product, improved market timing for planting and harvest, an increased opportunity for multiple cropping, and the possibility of growing higher value crops, the potential economic benefits to drip are significant.

The successful adoption of drip technology is a strategic business decision—not just a production decision. Growers with only a "production mentality" likely will fail to realize the full economic rewards from these activity complementarities. The growers with a clear understanding of these interdependencies can exploit them for their economic benefit by structuring their business around these complementarities.

5. CONCLUDING REMARKS

When starting a new farming operation, drip irrigation technology should be considered as an economically viable, alternative irrigation system. This form of precision or intensive agriculture creates economic opportunities beyond the production process. Growers that capitalize on these complementarities in their strategic planning will realize benefits in excess of those attributable to water savings and increased yields alone.

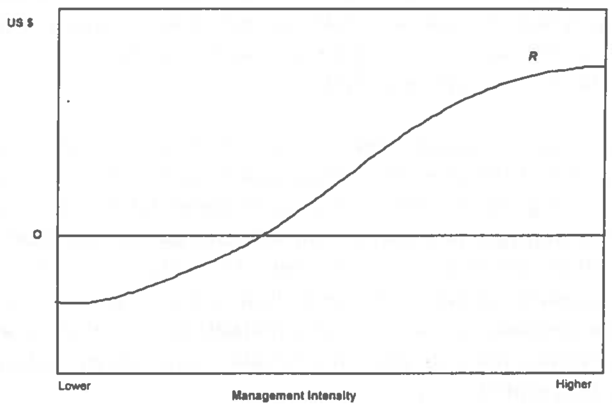


Figure 2: Profitability Differential Pattern (Net Present Value) Between Water Conserving (π_1) and Traditional Furrow (π_2) where $R=\pi_1-\pi_2$.

Growers with traditional irrigation technologies (flood, furrow, sprinkler) should cautiously evaluate the profitability of changing their water delivery system in light of the lessons learned over the last two decades. The preceding discussion has created an economic feasibility checklist of key variables or parameters for the adoption decision. From soil characteristics to yield increases to characteristics of the water source, the economic feasibility of drip irrigation technology is determined by both internal and external factors to the farm.

Two final summary points are clear from the literature and our experience in the Western United States. First, the economic gains associated with drip technology are largely attributable to the intensive management of the irrigation system. A simultaneous investment in human capital may be necessary to realize the advantages of a drip system. One of the most successful managers of drip irrigation systems in the U.S. earned two university degrees from a College of Agriculture and manages 405 hectares of melons virtually alone. He is well-compensated financially for his intensive management skills.

Finally, the adoption of drip technology requires a modern, farming systems mentality on the part of the adopter. Farming activities that once were considered independent of technology—procurement, labor management, and marketing for example—are now interdependent, creating economic opportunities in the marketplace. These complementarities realized through strategic thinking and coordination hold the greatest promise for significant net benefits to micro-irrigation.

REFERENCES

ANDERSON, D.P., WILSON, P.N. & THOMPSON, G.D. (1999). The adoption and diffusion of level fields and basins. *Journal of Agricultural and Resource Economics*, 24(1):186-203.

ANDERSON, T.L. (1995). Water options for the blue planet. In *The true state of the planet*. R. Bailey (ed.), The Free Press, New York. 267-294.

CASWELL, M. & ZILBERMAN, D. (1985). The choices of irrigation technologies in California. *American Journal of Agricultural Economics*, 67(2):224-234.

CLARKE, R, (1993). *Water: the international crisis*. MIT Press, Cambridge, Mass. 193 pp.

COUPAL, R.H. & WILSON, P.N. (1990). Adopting water-conserving irrigation technology: the case of surge irrigation in Arizona. *Agricultural Water Management*, 18:15-28.

COUPAL, R.H. (1985). *An economic evaluation of water harvesting technology*. Unpublished M.S. Thesis, Tucson, The University of Arizona. 97pp.

DAUBERT, J, & AYER, H. (1982). *Laser leveling and farm profits*. Technical Bulletin No. 244, Agricultural Experiment Station, College of Agriculture, Tucson, University of Arizona. 13pp.

FEDER, G., JUST, R.E. & ZILBERMAN, D., (1985). Adoption of agricultural innovations in developing countries: Asurvey. *Economic Development and Cultural Change*, 33:255-298.

FEINERMAN, E., & YARON, D. (1990). Adoption of drip irrigation in cotton: the case of kibbutz cotton-growers in Israel. *Oxford Agrarian Studies*, 18(1):43-51.

FISHELSON, G. & RYMON, D. (1986) *Adoption of agricultural innovations: The case of drip irrigation of cotton in Israel.* Foerder Institute for Economic Research Working Paper 35-86, Department of Economics, Tel Aviv University, Tel Aviv.

GLEICK, P.H. (1998). *The world's water.* Island Press, Washington DC, 307pp.

HARRIS, T.R. & MAPP, H.P. (1986). Stochastic dominance comparison of water-conserving irrigation strategies. *American Journal of Agricultural Economics*, 68:(2)298-305.

JAYAL, N.D. (1985). Destruction of water resources—the most critical ecological crisis of east Asia, *Ambio*, 14:96.

JENSEN, M.H. & MALTER, A.J. (1995). *Protected agriculture: a global review.* Technical Paper Number 253, The World Bank, Washington, DC. 156 pp.

MILGROM, P. & ROBERTS, J. (1990). The economics of modern manufacturing: technology, strategy, and organization. *American Economic Review*, 80(3):511-528.

NASH, L. (1993). Water quality and health. In GLEICK P.H. (ed.) *Water in crisis: A guide to the world's freshwater resources.* Oxford University Press, New York, 25-39.

PINDYCK, R.S. (1988). Irreversible investment, capacity choice, and the value of the firm. *American Economic Review*, 78(5):969-85.

POSTEL, S. (1997). *Last oasis: facing water scarcity.* WW Norton & Co., New York. 239pp.

POSTEL, S. (1999) *Pillar of sand: Can the irrigation miracle last?* WW Norton & Co., New York. 313 pp.

SHAW, F.A., ZILBERMAN, D., & CHAKRAVORTY, U. (1995). Techology adoption in the presence of an exhaustible resource: The case of groundwater extraction. *American Journal of Agricultural Economics*, 77(2):291-99.

SHRESTHA, R.B. & GOPALAKRISHNAN, C. (1993). Adoption and diffusion of drip irrigation technology: an econometric analysis. *Economic Development and Cultural Change*, 41(2):407-418.

SIMON, P. (1998). *Tapped out: the coming world crisis in water and what we can do about it.* Welcome Rain, New York. 198pp.

WILSON, P.N., AYER, H.W. & SNIDER, G. (1984). *Drip irrigation for cotton: Implications for farm profits.* Economic Research Report No. 517, USDA/Economic Research Service, Washington, DC. 29pp.

WILSON, P.N., COUPAL, R.H. & HART, W.E. (1987). *An economic evaluation of linear move irrigation technology.* Technical Bulletin No. 258, Agricultural Experiment Station, College of Agriculture, University of Arizona, Tucson. 20pp.

WILSON, P.N., FOX, R.W. & WILLETT, G.S. (1976). *The economics of pressurized irrigation systems for mature citrus orchards in southwestern Arizona.* Technical Report No. 14, Department of Agricultural Economics, The University of Arizona, Tucson. 76pp.