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# CANALS and COMMUNITIES

## Small-Scale Irrigation Systems

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# The Relevance of Indigenous Irrigation

## A Comparative Analysis of Sustainability

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In the latter half of the twentieth century, international agricultural development efforts have invested heavily in irrigation because of its proven abilities to expand cultivated areas and to increase yields on existing croplands. The overwhelming emphasis of these investments has been on what can be described as "industrial irrigation," systems that are developed in industrialized countries and introduced to nonindustrial ones. These systems rely on mechanization, increased energy and capital inputs, large-scale physical infrastructures, centralized management, and fewer crops bred to be more responsive to agrochemicals and increased water supplies.

The many traditional systems of irrigated agriculture that are being replaced can be described as "indigenous irrigation," systems that are locally developed by cultures with unique histories, often over long periods of time, and usually relying on intensive human labor, small-scale water control systems, direct farmer management, and a diversity of crop varieties adapted to local environments. Today, most indigenous irrigators use a mixture of traditional and modern technologies and techniques, and are at least partially linked to national, regional, and global markets. Many indigenous irrigation systems have also been incorporated into larger, state-managed, industrial irrigation systems. Where an adequate degree of local autonomy has been maintained, however, indigenous irrigation systems retain enough of their local adaptations to remain distinctive from industrial systems.

Our purpose in this chapter is to reassess a few conventional wisdoms about the differences between these two types of irrigated agriculture, introduce some new hypotheses, and carry out preliminary tests with some of the available data. Our theory is that indigenous systems of irrigated agriculture are more ecologically and socially sustainable over the long term. Three general hypotheses based on this theory are discussed in the following sections: On average, indigenous systems of irrigated agriculture are (1) more efficient in the use of energy, capital, and natural resources; (2) have more stable yields over the long term; and (3) are more equitable in terms of opportunities, benefits, and risks. We test these hypotheses by reviewing comparative data on relative efficiency, stability, and equity (basic properties of agroecosystems, and essential components of sustainable economies), and suggest some additional data that may be needed to fully assess them. If comparisons among existing data and from future investigations support acceptance of these hypotheses and more specific versions, then we can conclude that indigenous irrigation systems hold useful lessons for the development of sustainable agriculture.

## Efficiency

Comparative data indicate that in both nonirrigated and irrigated agriculture the efficiencies of the primary factors of agricultural production are inversely related, there are limits to their substitutability for each other, and the relative returns to the substituting factors of industrial agriculture decline over time. These patterns and trends lead us to hypothesize that indigenous irrigated agriculture is less labor efficient than industrial irrigated agriculture, but makes more efficient use of energy, capital, and natural resources. In the following we show how these differences are obscured by simplistic conventional economic calculations, but are obvious when true values and additional relevant variables are included.

### Hidden Costs of Conventional Economic Efficiency

When applied to agriculture, efficiency, as defined by conventional neoclassical economics in terms of benefits relative to costs, discounts long-term returns from soil, water, and other agricultural resources in favor of short-term yields and profits (Norgaard and Howarth 1991). An example is the practice of pumping groundwater at rates in excess of natural recharge rates, as is done on one-fifth of the irrigated land in the United States (Brown and Young 1990). Also, many costs are not included in benefit-cost accounting of agriculture and irrigation. Economic costs are hidden by subsidies, and environmental and social costs are either considered too long-term to be relevant, are removed as "externalities," or are not even acknowledged (Daly and Cobb 1989).

The total costs of industrial irrigated agriculture are often hidden by government use of general tax revenues to subsidize between half and all of the costs of construction and water delivery on large irrigation projects (Sagardoy 1982; Repetto 1986; World Bank 1992). In the 1980s, all of the costs of construction were subsidized on government irrigation projects in Indonesia, Malaysia, Vietnam, Australia, Peru, Saudia Arabia, and South Africa, while between 80 and 100 percent of all water costs were waived in government irrigation schemes in China, India, Pakistan, Indonesia, Mexico, Bangladesh, Egypt, and the Philippines. An average of 60 percent of construction costs, and 60 to 99 percent of water costs, were subsidized on federal irrigation projects in the United States during that decade. This makes industrial irrigated agriculture appear more economically competitive than it would be if the benefiting farmers had to assume complete costs at true market values.

Soil salinization, cropland loss, water contamination, population displacement, increasing incidence of disease, and other long-term costs of industrial irrigation are usually not adequately estimated, but are beginning to outweigh the short-term benefits on a global scale. Salinization resulting from overirrigation and poor drainage has significantly reduced yields on more than 60 million hectares world-wide, about a quarter of the total area irrigated, and 25 million hectares have been abandoned because of salt accumulation (World Resources Institute 1992). Annually, for every additional hectare brought into production by new irrigation schemes, another goes out of production because of salinization (Umali 1993). "Superdams" constructed on major rivers in Africa since 1950 have displaced more than a quarter of a million people, and destroyed their traditional subsistence base of flood recession agriculture (Scudder 1989). It is estimated that Pakistan's Kalabagh Dam will uproot 234,000 people, and adversely affect the water quality and supply of fifteen to twenty million more (Gazdar 1990). Resettlements of about a million people each will be necessary to complete dams on the Yangtze River in China (Ryder 1988) and the Narmada River in India (Alvares and Billorey 1988). Associated with construction of large reservoirs and permanently flowing canals are increased incidence rates of diseases and infections spread by water-borne parasites and other vectors, including malaria, schistosomiasis (bilharzia), liver flukes, filariasis, onchocerciasis (river blindness), dengue fever, yellow fever, chikungunya fever, and encephalitis (Sheridan 1984; Oomen, deWolf, and Jobin 1988). Around the world, a wide variety of successful indigenous modes of subsistence, including irrigated farming systems, are being replaced by industrial irrigation at enormous environmental, social, and health costs that are seldom included in long-term cost projections.

### Limited Substitutability of Factors of Production

The neoclassical economic model of agriculture considers land, labor, and capital as the primary resources or "factors" of production, assumes that each can be almost infinitely substituted for any other, and focuses on their changing relative costs in a market-driven search for economic efficiency measured in terms of productivity and profit. The elegant simplicity of this conventional model is also its greatest weakness. It collapses within the single category of capital equally important factors of production such as technology, while cultural knowledge of environments and farming techniques are ignored altogether. It also subsumes energy and other natural resources within the category of land, reduces the contribution of land to rent (and rent to a surplus that is excluded from price determinations), and assumes that if production falls due to reduction in the quality or quantity of land, that production can be maintained or increased by substituting capital or labor (Daly and Cobb 1989).[1]

Daly (1990) proposes that the distinction between natural capital and human-made capital is important, and that their substitutability for each other is ultimately limited. For example, because harvest rates cannot exceed natural regeneration rates to maintain sustained yields, and rates of waste emission cannot overwhelm the absorption capacities of ecosystems, these regenerative and assimilative capacities of ecosystems should be treated as forms of "natural capital," as the failure to maintain them represents unsustainable capital consumption. Capital and labor are relatively substitutable for each other because they both function to transform resources into products, but they cannot significantly substitute for natural capital because the materials transformed and the tools of transformation are complements in their production roles, not substitutes (Daly 1990; see also El Serafy 1991).

### Inverse Efficiencies of Factors of Production

In the irrigated form of industrial agriculture, capital and energy are substituted for labor and/or water, with the costs of substituting resources increasing as the costs of those being substituted for decrease. Data from studies of irrigation in the western United States during the late 1970s and early 1980s (Batty and Keller 1980; Roberts, Cuenca, and Hagan 1986) show that decreases in labor or water costs tend to be balanced by an increase in capital and/or energy costs. For example, if labor-intensive hand-moved sprinklers are compared to labor-efficient drip lines, each hour of labor saved per hectare corresponds with a savings of 22.5 cubic meters of water and .346 gigajoules of energy, along with higher operating costs of $9.69 (when installation costs are included, these inverse correlations are magnified until investments are paid off). The data indicate that increased efficiencies of one kind are largely offset by decreased efficiencies in the other factors of production.

In contrast to these trends in industrialized countries (see also Ruttan 1984; Barlett 1989), the diffusion of the industrial system of agriculture to other parts of the world has boosted land productivity only at the costs of increased labor, water, and energy. In regions where capital-intensive mechanization was not affordable for farmers, the necessary higher applications of water, fertilizers, and pesticides associated with adoption of modern crop varieties has led to higher labor inputs to realize the same yields. Studies of twenty different regions in South Asia, Southeast Asia, and Indonesia conducted in the early years of the Green Revolution, between 1966 and 1975, found that paddies planted in modern rice varieties required an average of 22 percent higher labor per hectare than did fields growing traditional varieties (Barker and Herdt, with Rose 1985:127). In these regions the increased land productivity made possible by Green Revolution technology was offset by decreased productivity per unit of labor. This is the same kind of agricultural "involution" described by Geertz (1963) for the intensification of wet rice production in Indonesia prior to the Green Revolution, which raises some important questions about the real-versus-predicted effects of the Green Revolution on labor efficiency.

### Declining Returns to Industrial Inputs

Even in regions where efficiencies of one or more production factors have increased, declining economic returns to capital and energy inputs—the substituting factors of industrial agriculture—are becoming apparent. Marginal production response to fertilizer applied to a U.S. cornfield or

Indonesian rice paddy is only half as much as twenty years ago (World Resources Institute 1990). Yields of modern wheat varieties have not changed since 1970 in Pakistan's Punjab region (despite an increase in fertilizer use from 40 to 114 kilograms per hectare), while the marginal increase in grain production from each kilogram of fertilizer applied has fallen to less than 5 to 1 in other parts of Pakistan, compared to over 10 to 1 in the first years of the Green Revolution (Byerlee 1990). After some initial success, pesticides have also lost their effectiveness. Before the use of modern agrochemicals, about a third of the world's annual harvest was lost to insect pests and weeds. Today, while the numbers of pest species known to be resistant to insecticides and herbicides have increased a hundred-fold, the proportion of the crop lost is about the same or greater (Dover 1985). As per capita grain production has leveled off, so have economic returns to the crop varieties, inputs, and methods of industrial agriculture in some of the world's most densely populated countries, including India, Indonesia, Taiwan, South Korea, Japan, China, and Mexico (Brown and Young 1990). Some see this as an indication that the period of dramatic increases in food production due to the Green Revolution may be over, while the costs of industrial agriculture continue to climb and the supporting fossil fuel reserves rapidly dwindle (Brown and Young 1990; Cleveland 1990).

## Ratios of Total Energy Outputs to Inputs

Aside from the problems with how benefit-cost ratios are calculated, the difficulty of measuring long-term human and environmental costs, and the inaccuracy of the assumption of unlimited substitutability of production factors, ecologists' calculations of total energy inputs and outputs show that the energy efficiencies of industrial agricultural systems are often negligible, and have declined through this century. Time-series analysis of total energy output relative to the sum of energy inputs (direct fuel and electricity costs plus indirect energy costs of infrastructures, labor, and manufactured inputs such as agrochemicals) in U.S. agriculture between 1910 and 1988 shows that indirect fossil fuel use dominated direct use, with energy efficiency declining rapidly between 1910 and 1973 as total energy use increased more than 500 percent, and then increasing efficiency between 1974 and 1988 as total energy use decreased 42 percent (C. Cleveland 1991).[2]

World-wide comparisons, meanwhile, show that the impressive yields of industrial agriculture, derived from intensive use of manufactured, fossil fuel-based inputs, represent lower energy efficiency relative to less industrialized systems of agriculture (Cox and Atkins 1979; Pimentel and Pimentel 1979). This contrasting pattern is also apparent in comparisons of ratios of energy outputs to inputs in different irrigated systems (table 11.1). An irrigator in the Ziz Valley oasis of southern Morocco, for example, invests sixty-four times more manual labor than his California counterpart to produce a wheat yield of up to 4,000 kilograms per hectare, but he uses less than half as much petroleum inputs in the forms of agrochemicals and fuel for machinery (Mabry, Ilahiane, and Welch 1991). The Moroccan's crop yield thus represents a ratio of energy return of up to 12.3 to 1, while the Californian's average crop yield of 4,640 kilograms per hectare represents a relatively meager energy return of 7.3 to 1 (Pimentel and Pimentel 1979). Maize crops produced from raised and drained *chinampa* fields in the Valley of Mexico represent an impressive return of 103.4 to 1 (Sanders and Santley 1983), while irrigated rice production in California has one of the lowest energy output-to-input ratios in world agriculture: 1.4 to 1 (Pimentel and Pimentel 1979). Traditional systems of flood recession agriculture, which rely on "natural irrigation," also have relatively high potential energy efficiencies: up to 102.5 to 1 for riverbank maize production in southern Belize (Wilk 1985); 71.7 to 1 for floodplain rice production along rivers in the upper Amazon Basin in Peru (Chibnik 1990); and 152 to 1 for sorghum cropping on the alluvium of the Senegal River (Park 1992).[3]

## Economies of Scale in Irrigation and Agriculture

Increasing farm sizes and a search for economies of scale are also significant trends in the development of industrial agriculture. Here again, direct and indirect state subsidies of production costs and discounting of future returns distort both market processes and measurements of agricultural efficiency. For example, in the western United States, despite the provision in the 1902 Reclamation Act limiting use of water from federal water projects to 160 acres (65 hectares) per farmer, or 320 acres (130 hectares) per married couple, farmers were at first able to avoid breakup of their large holdings by irrigating the legal amount with federal water and pumping free groundwater for the remainder (Worster 1985). By midcentury, though, the provision was interpreted more loosely by the Bureau

**Table 11.1** Energy inputs and outputs in indigenous and industrial irrigated grain production, 1975–1985.

| Grain and Type of agriculture | Location | Inputs |  |  |  |  |  |  | Outputs |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Human labor |  | Animal labor | Fertilizers[1] |  | Fossil-fuel based[2] | Total energy input | Grain yield | Labor productivity | Total energy output | Energy return ratio |
|  |  | hrs/ha | kcal/ha[a] (× 000) | kcal/ha[b] (× 000) | kg/ha | kcal/ha[c] (× 000) | kcal/ha (× 000) | kcal/ha (× 000) | kg/ha | kg/hr | kcal/ha[d] (× 000) | kcal output/input |
| **Maize** |  |  |  |  |  |  |  |  |  |  |  |  |
| Recession | Southern Belize | 448 | 67.2 | — | — | — | — | 67.2 | 230–1,940 | .5–4.3 | 816.5–6,887.0 | 12.1–102.5 |
| Floodwater | Central Mexico | 100 | 25.0 | 594.0 | — | — | — | 619.0 | 800–1,000 | 8.0–10.0 | 2,840.0–3,550.0 | 4.6–5.7 |
| Canal irrigation | Central Mexico | 153 | 78.8 | 594.0 | — | — | — | 672.0 | 1,000–1,400 | 6.5–9.1 | 3,550.0–4,970.0 | 5.3–7.4 |
| Sprinkler irrigation | Western U.S. | 12 | 5.6 | — | 280 | 2,225.6 | 6,526.5 | 6,532.1 | 5,390 | 449.5 | 19,134.5 | 2.9 |
| Raised-drained field | Central Mexico | 200 | 103.0 | — | — | — | — | 103.0 | 3,000 | 15.0 | 10,650.0 | 103.4 |
| **Wheat** |  |  |  |  |  |  |  |  |  |  |  |  |
| Recession | Egypt, pre-Aswan Dam | 555 | 83.2 | 1,926.0 | — | — | — | 2,009.2 | 570–2,850 | 1.0–5.1 | 1,892.0–9,462.0 | .9–4.7 |
| Canal irrigation | Ziz Valley, Morocco | 449 | 231.2 | — | 95 | 807.5 | 848.9 | 1,080.1 | 1,346–4,000 | 3.0–8.9 | 4,468.7–13,280 | 4.1–12.3 |
|  | Eastern Jordan Valley | 520 | 267.8 | — | 34 | 289.0 | 330.4 | 598.2 | 2,500–4,500 | 4.8–8.6 | 8,300.0–14,940.0 | 13.9–25.0 |
|  | Uttar Pradesh, India | 615 | 316.7 | 1,926.0 | — | — | 41.4 | 2,284.1 | 1,600 | 2.6 | 5,312.0 | 2.3 |
| Sprinkler irrigation | Western U. S. | 7 | 3.2 | — | 106 | 841.0 | 2,112.4 | 2,115.7 | 4,640 | 562.9 | 15,404.8 | 7.3 |
| **Rice** |  |  |  |  |  |  |  |  |  |  |  |  |
| Recession | Upper Amazon, Peru | 634 | 95.1 | — | — | — | — | 95.1 | 2,000 | 3.1 | 6,820.0 | 71.7 |
| Canal irrigation | Lowland Philippines | 1,864 | 960.0 | 952.0 | 30 | 280.0 | 321.4 | 2,276.9 | 2,050 | 1.1 | 6,990.0 | 3.1 |
|  | Eastern China | 1,048 | 539.7 | 952.0 | 195 | 3,616.3 | 1,639.9 | 3,131.7 | 3,770 | 3.6 | 12,885.7 | 4.1 |
|  | Lowland Japan | 1,128 | 524.5 | — | 431 | 1,639.9 | 6,721.7 | 7,246.2 | 5,710 | 5.1 | 19,471.1 | 2.7 |
|  | Western U.S. | 12 | 7.9 | — | 347 | 2,859.4 | 14,431.6 | 14,439.5 | 6,160 | 362.3 | 21,005.6 | 1.4 |
| **Sorghum** |  |  |  |  |  |  |  |  |  |  |  |  |
| Recession | Senegal Valley, Mauritania | 300 | 45.0 | — | — | — | — | 45.0 | 400–2,000 | .5–2.5 | 1,368.0–6,840.0 | 30.4–152.0 |
| Sprinkler irrigation | Western U.S. | 12 | 5.6 | — | 119 | 1,000.8 | 5,372.6 | 5,376.1 | 3,030 | 252.5 | 10,362.6 | 1.9 |

(1.) Nitrogen, phosphorous, potassium

(2.) Machinery, fuel, fertilizers, pesticides, drying, transportation

(*a*.) Recession: 150 kcal/hr; floodwater: 250 kcal/hr; canal irrigation/raised-drained field: 515 kcal/hr; industrial canal/sprinkler irrigation: 465 kcal/hr

(*b*.) Animal labor: 3000 kcal/hr

(*c*.) Nitrogen: 14,700 kcal/kg; phosphorus: 3000 kcal/kg; potassium: 1600 kcal/kg.

(*d*.) Maize: 3550 kcal/kg; wheat: 3320 kcal/kg; rice 3410 kcal/kg; sorghum 3420 kcal/kg.

*Sources:* Pimentel and Pimentel 1979; Wilk 1985; Sanders and Santley 1983; Stanhill 1984; Barker, Herdt, and Rose 1985; Chibnik 1990; Qasem 1990; Mabry, Ilahiane, and Welch 1991; World Resources Institute 1992; FAO 1991; Park 1992 of Reclamation, when the 160-acre allotment was extended to every adult member of a farm household, and time limits on leasing were ended. In this case, an economy of scale was obtained by the larger farms of the western United States through greater use of subsidized water from federal projects, unregulated individual use of common property water resources, or both.

In addition to the distorting effects of subsidies and discounting, the pattern found through cross-cultural comparisons challenges the economies-of-scale model by suggesting that productivity (output per unit of land area over time) and efficiency (ratio of output per unit of input over time) may be inversely related to the scale of production units (sizes of fields and farms). This possibility is usually overlooked in industrial countries due to the belief that smallholder production is less efficient than large-scale agribusiness, and in developing countries due to the need to rapidly boost national productivity. According to studies in India, however, irrigated agriculture increases in productivity as the size of farms decreases (Saini 1979). World-wide, in fact, there is an inverse relationship between area cultivated and yield in all types of agriculture; on average, smallholders get more out of the same amount of land (Berry and Cline 1979; Netting 1993). Strange (1988) has concluded from comparative data that, even in the United States, where farmers take pride in the labor efficiency of their large operations, smaller and medium-size farms are more efficient in resource use, their production costs relative to gross sales are lower, and their profits as a percent of gross sales are higher.[4]

### Management Structure and Administrative Efficiency

Comparative data suggest that, in addition to the scale of production units, efficiency and productivity in irrigated agriculture is related to management structure, or the locus of resource control. Because their administration is less efficient in terms of information flow and decision making, centrally managed systems have lower productivities than locally managed ones. Ostrom (1993), in her comparisons of 108 irrigation systems in Nepal, found that farmer-managed systems averaged crop yields of 6 metric tons per hectare, compared to 5 metric tons per hectare on agency-managed systems. The tendency of centrally managed systems toward lower productivity is probably related, at least partly, to the logistical difficulty of efficiently monitoring and directing multiple local units within large-scale systems from single, distant locations.

### Efficiency and Irrigated Agricultural Production

The studies cited and our comparisons seem to support our hypothesis concerning efficiency in irrigated agriculture. The data show inverse trends in the efficiencies of different agricultural resources in the transformation to the industrial mode of agricultural production, declining returns over time to the substituting factors of industrial agriculture (capital and energy), and relatively low efficiency in terms of the ratio of total energy outputs to inputs in industrial irrigated agriculture. The data also indicate that smaller farms and locally controlled irrigation systems tend to be more efficient and productive than larger farms and centrally controlled systems.

We suggest that these patterns indicate limitations to the substitutability between primary factors of agricultural production, highlight how agricultural efficiency is measured in conventional economic models, and challenge the applicability of economy-of-scale models to farming. This does not mean, however, that industrial irrigated agriculture is less productive over the short term, or is inefficient in terms of labor or even water use in the case of some application systems; we are only pointing out its hidden costs, tradeoffs, and negative long-term rates of return that are not usually considered. More complete accounting, along with a comparative perspective, will allow further testing of our hypothesis that the kinds of efficiency found in indigenous systems of irrigated agriculture, including those kinds not usually measured, are related to their appropriate technologies, small scales, and local institutions for resource control.

## Stability

In agriculture there is evidence for a causal and inverse relationship between stability and productivity at the biological, ecological and sociocultural levels, which is mediated, to a large degree, by diversity (Cleveland 1993, 1995). Because indigenous agriculture tends to be more biologically, ecologically, and socially diverse than industrial agriculture, it is logical that the replacement of indigenous irrigation by industrial irrigation, as part of the industrialization of agriculture, increases instability. This deduction, supported by comparative data, leads us to hypothesize that industrial irrigated agriculture has less stable yields than indigenous irrigated agriculture. Initially, it may seem illogical to suggest that supplying water by irrigation to crops formerly dependent only on unreliable rainfall would decrease yield stability. As we hypothesize, however, it is not irrigation per se that increases instability, but rather the tendency of industrial irrigation to increase irrigation intensity, diminish biological diversity, and decrease local management that account for the tendency of irrigation to decrease yield stability.[5]

## Irrigation Intensity

The intensity of irrigation, measured as the amount of water applied in a given area over a given time period, which includes expanding irrigated lands in a country or region, tends to increase with industrialization. This usually involves an increase in cropping intensity and a shift to more water-consumptive crops, both of which raise the demand for water per unit area, as well as demand for other inputs such as chemical fertilizers and pesticides. Comparative data suggest that, rather than the irrigation per se, the increased use of these related inputs and of water-responsive modern crop varieties decreases yield stability.

Most quantitative analysis of yield stability has been done on short-term variability and on comparison of periods before and after the development or introduction of industrial agriculture (Anderson and Hazell 1989). In one of the first reports to specifically examine yield stability in relation to irrigation, it was argued that "there is no evidence to support" the assertions made in the Green Revolution literature that modern technology, including industrial irrigation infrastructures, leads to increased yield stability (Barker, Gabler, and Winkelmann 1981:74). Comparative data were used to show that, although irrigation may potentially reduce moisture stress, it is frequently associated with an intensification of crop production and input use that is "destabilizing" (Barker, Gabler, and Winkelmann 1981:63). In a shift to industrial wheat production producing 63 percent higher yields, for example, irrigated farms in the Yaqui River valley of Mexico experienced a 45 percent increase in yield variability (measured by standard deviation), to a level higher than that measured for rainfed industrial wheat production in Nebraska, United States (Barker, Gabler, and Winkelmann 1981:59). A comparison of data from East Asia with the evidence from South and Southeast Asia supports this general hypothesis of an inverse relationship between industrialization of irrigation and yield stability. Barker, Gabler and Winkelmann (1981:64–65) conclude that the data show higher absolute variability but about the same range of relative variability in East Asia, which had "the most highly developed infrastructure and the highest yields" of rice.

Many other researchers have identified the same trend.[6] Mehra (1981) has compiled data on variability in food grain yields in rainy (*kharif*) and dry (*rabi*) seasons in India, revealing that variability tends to be higher during the rainy season, when a smaller proportion of the cultivable area is irrigated. She interprets this as showing that "irrigation by itself appears to reduce yield variability," but "when irrigation is combined with intense input use, yield increases, but so does variance" (Mehra 1981:30). She also found that the absolute variation (standard deviation) for all crops increased by 75 percent, and for food grains by 65 percent, from the period before the Green Revolution, when local crop varieties predominated.

Although confirming Mehra's findings, Hazell's (1982) reanalysis suggests that the nearly 50 percent increase in relative instability between pre- and post-Green Revolution periods, from 4.03 to 5.85, was due primarily to increasing covariation of yields of different crops in the same state and between states, rather than increases in crop yield variances per se. In either case, it is the synergistic movement toward modern crop varieties more responsive to increased supply of water and other inputs and the intensification of production and inputs (both typical of industrial irrigation) that leads to increased instability.[7]

## Water Supply

Increasing irrigation intensity is associated with increasing exploitation of water supply, as more sources are tapped at greater rates of use. Thus, the stability of water supply is a major factor affecting yield stability. Mehra (1981:37) believes that the evidence from her study of variability in Indian food grain production shows that "when seed-fertilizer technology is combined with assured irrigation, the tendency for variance to increase is neutralized." In the real world, however, farmers seldom receive the optimal amount of water at the right time to obtain the potential yields of industrial crop varieties. For example, Walker (1989) has shown that in

India, irrigation tends to increase covariance between regions for sorghum yields, but leads to reduced interregional covariance for millet yields. He concludes that "this puzzling result could stem from the fact that irrigated pearl millet often entails only one or two applications of water and is largely cultivated where water supply is most uncertain" (Walker 1989: 99). Variability in water supply, then, may explain this pattern for millet.[8]

As more accessible surface water supplies are allocated, irrigation systems tend to exploit groundwater, often at unsustainable rates, thereby stabilizing yields over the short term, but only by decreasing long-term stability. With fossil fuels, groundwater is pumped from deep tubewells—an industrial technology widely adopted in nonindustrial countries—to provide almost all of Libya's and Saudi Arabia's water supplies, 95 percent of Tunisia's, and 75 percent of Israel's and Iran's (Postel 1989). By the mid-1980s, tubewells supplied 40 percent of the irrigated area in Bangladesh, and falling water tables and resulting saltwater intrusion has raised pumping costs and reduced water quality (Mandal 1987). Because of overpumping, groundwater levels are falling between 1 and 2 meters per year in parts of northern China, and 2.5 to 3 meters per year in the southern Indian state of Tamil Nadu; more than 4 million hectares in the United States (about 20 percent of the total irrigated area) is supplied by pumping in excess of natural recharge rates (Postel 1992).

### Biological Diversity

An important corollary of increasing irrigation intensities and increasing rates of water resource exploitation is often the substitution of more water-consumptive crops and modern crop varieties for local farmers' or folk crop varieties.[9] In fact, the spread of the Green Revolution in the Third World has largely been limited to the irrigated zones, and modern crop varieties have not performed well in marginal, rainfed areas of Asia, Africa, and Latin America, where more dependable local varieties still predominate (Chambers 1984a; Barker and Herdt, with Rose 1985). Decreasing crop genetic diversity may also contribute to destabilization of irrigated agriculture. For example, among ten Asian countries analyzed for before- and after-Green Revolution periods, "there was a tendency for the percent of area in modern varieties, yield, standard error, and coefficient of variation to increase with a rise in the percentage of irrigated rice area" (Barker, Gabler, and Winkelmann 1981:63). Plant breeders and agronomists often find that crop yield cannot be increased without decreasing the stability of yield when the crop is exposed to drought, waterlogging, pests and pathogens, and other stresses. Although few comparisons between folk varieties and modern varieties have been carried out, existing data suggest that modern varieties often have higher yields than folk varieties under optimal conditions, while heterozygous and heterogeneous folk varieties with broad resistance to a variety of stresses often have higher production than modern varieties under stress (Cleveland, Soleri, and Smith 1994).

It is not only through decreasing biological diversity that the spread of modern varieties may destabilize irrigated agriculture, but also through the high costs of other necessary inputs. Pandey (1989:236) notes that, because irrigation is often part of a package that includes modern varieties and fertilizers, it "increases the marginal productivity of other complementary inputs," leading to "more intensive cropping practices." In the case of modern varieties, this means that Third World farmers must often buy a whole package of industrial inputs from distant sources. Uncontrollable interruptions of supply, along with difficulties in obtaining credit and unpredictable variations in annual incomes, also lead to yield instability when agricultural inputs must be purchased rather than locally obtained.

At the ecological level, beginning in the field, the diversity of traditional agriculture in the form of many crops and many varieties of each crop, and diversity in soil conditions and field locations may often result in higher yield stability than demonstrated in uniform, industrial agroecosystems. Intercropping tends to increase yield stability (Lynam et al. 1986), and, although there are some exceptions (for example in China), irrigation leads to a significant increase in monocropping (Jodha 1990). The spread of uniformity across the landscape in the form of similar crops and crop varieties, planting patterns, inputs, and government agricultural price supports, all of which usually accompany the spread of intensive industrial irrigation, tend to increase the covariation or synchrony between crops and between regions. Along with greater instability of modern varieties per se under stressful conditions, this covariation contributes to yield instability (Anderson and Hazell 1989, Hazell 1989).

### Management Structure

At the social level, there is support for the hypothesis that centralized management structure causes an increase in yield instability by removing the ability and power of farmers and local communities to manage irrigation in response to changing local conditions. A number of social scientists investigating irrigation systems believe that increasing centralization of water distribution leads to a process of positive feedback that drives a centralizing trend to the point where production is pursued in almost complete isolation from environmental and local level social pressures, leading inevitably to a system crash (Merrey 1987; Swearingen 1987; Chambers 1988:239–242; Cleveland 1996, Uphoff, Wickramasinghe, and Wijayaratna 1990; Wade 1986). In international agricultural development, the failure of projects planned and administered in ignorance of local systems, as most have been, is legend.

In systems that centralize water control in the hands of headenders, the problems of tailenders resulting from decreased adequacy, reliability, and timeliness of water supplies are well-known, but Chambers describes a frequent, but less-recognized, problem among headenders in Asian irrigation systems: "Quite often, headreach farmers appear to be locked into their own variety of the tragedy of the commons. This is especially marked with field to field irrigation of paddy. The abundant issue of water and consequent flooding, combined with the cultivation of paddy by his neighbors, remove any option from a farmer to grow anything but paddy; and then because all farmers follow this practice, waterlogging, salinity, and flooding ensue, reducing or eliminating yields" (Chambers 1984b:41).

Community management of common property resources such as irrigation water sources and delivery systems may increase yield stability by managing for long-term conservation (sustainability), and these common property management institutions are more likely to evolve and persist where viable, local communities with control over local resources already exist. A review of a number of independently conducted case studies of common pool resource management supports the theory that irrigation water and other common property resources tend to be managed by local community groups such as water users' associations when there is a common understanding of problems and alternative solutions, when decision-making costs are less than benefits, and when local organizations are nested in a hierarchy of organizations that protects them from external forces such as government interference, market fluctuations, and population pressure (Ostrom 1992, 1993).

The effect on stability of industrial irrigation in increasing central management and simultaneously reducing local control is illustrated by the Salinity Control and Reclamation Projects (SCARPS) of South Asia. SCARPS are attempts to salvage large-scale industrial irrigation systems from production problems by further application of the same central management industrial development approach that created the problems in the first place. SCARPS are dominated by engineers who see "physical, hardware remedies . . . as the *only* remedies," and completely ignore obvious solutions, such as supplying less water (Chambers 1988:78, emphasis in original). For example, in the Swabi SCARP in northwest Pakistan, water-user associations and a demand system were proposed as ways to increase production by increasing farmer participation, but their design and application tend to decrease participation and increase instability (Cleveland 1996). In fact, the main purpose of water-users' associations seems to be to force the irrigators to carry out the program planned for them by the central bureaucrats. As with most conventional irrigation development in Pakistan, this project also ignores farmers' agricultural expertise and their knowledge of the irrigation system.

### Stability and Irrigated Agricultural Production

Overall, the available data do appear to support our hypothesis that the increasing intensity, decreasing biological diversity, and centralization of management that accompany the industrialization of irrigation tend to increase variability in yield compared with indigenous irrigation. Although the effect of irrigation on yield stability depends on the timing, season, and predictability of the water supply, irrigation generally increases absolute variability because of the associated increases in yield, planting of water-responsive modern crop varieties, homogeneity of the growing environment, and covariance between neighboring fields. Efforts to assure the reliability of irrigation water over the short run, such as increased extraction from the source (larger dams or deeper tubewells, for example), are also likely to lead to larger fluctuations or even failures in the water supply over the long term, due to depletion of aquifers, siltation of reservoirs and canals, waterlogging and salinization of fields, and a centralized administration increasingly inattentive to feedback from local ecological and social conditions.

Despite general support for our hypothesis, the data considered here are not entirely consistent, and no predictive statements are yet possible that apply to specific situations. Yield stability covaries with other factors besides the degree of agricultural industrialization, as for example, in a comparison of data from Bihar and Tamil Nadu states in India (Barker, Gabler, and Winkelmann 1981:63). Our hypothesis predicts that, because yields are twice as high in Tamil Nadu, variability should also be higher—yet the data show the opposite, probably because of the high frequency of severe floods and droughts in Bihar. To accurately compare stability and yield, therefore, environmental disturbances must be experimentally or statistically controlled. Pandey (1989:241) also points out that the evidence for the effects of irrigation on production variability is inconclusive because the conventional production function treats irrigation as a constant and homogeneous input, when in fact the effect of irrigation depends on the "quantity applied, the timing of application, stability of water supply, water distribution rules, plant characteristics" and relationships that are "dynamic, interactive, and stochastic." There does appear to be sufficient evidence, however, to cast doubt upon the conventional wisdom that yields are stabilized through industrialization of irrigation, including increased irrigation intensity, adoption of modern crop varieties, and central control over water and other inputs.

## Equity

In irrigation systems, the equity of water allocation can be assessed in terms of how close the actual distribution fits a culturally defined ideal such as temporal priority of use, proportionality to land holdings or labor contributions, or variation among users in areas irrigated, field soil moistures, crop yields, or farming incomes. In farmer-managed irrigation systems, equity is often measured in terms of risk-spreading or wealth-leveling among system users. But cultural differences mean that equity is inherently subjective; in many places, there are rules for regulating use of water resources that reflect cultural concepts of equity, yet at the same time result in advantageous arrangements for some socioeconomic groups or classes. Indeed, established inequalities are often reinforced by the customary rules of resource access, or by local political structures. Differential access to naturally flooded land in Somalia maintains the stratification of power (Besteman, chapter 3). In some areas of Mexico, water is allocated according to the political connections of local bosses, who thereby increase their power (Yates 1981).

Clearly, equity—like beauty—lies in the eye of the beholder; it cannot be measured objectively by a single personal or cultural criterion. Yet, comparative data leads us to hypothesize that, whether equity within a group of irrigators is measured in terms of relative evenness in access to the means of production (irrigable land, water supplies, delivery systems), obligations for contributions to construction and maintenance (labor, capital), distribution of benefits (yields, profits, employment), or shares of risk (water shortages, pest infestations, and so on), indigenous irrigated agriculture tends to be more equitable than industrial irrigated agriculture.

### Contributions and Benefits

In addition to rules specifying use rights, rules regarding the relationship between labor or capital contributions and the distribution of benefits also determine the relative equity of an irrigation system. For example, in a system that assigns equal shares of water to each household but requires all males to contribute labor, larger households have to contribute a disproportionate amount of labor; this outcome can be avoided by allocating water in proportion to labor inputs (Ostrom 1993). Irrigation systems with unequal distributions of benefits do not function as well as systems in which benefits are distributed in ways considered equitable by a majority of users. For example, systems that result in unequal distribution of benefits have lower rates of compliance to rules. In a comparison of forty-three case studies of community irrigation systems, Tang (1992) found that systems with higher variance in average annual family incomes demonstrated lower degrees of rule conformance and fewer contributions to maintenance.

### Headender-Tailender Relationships

The relative positions of irrigators within the hierarchical management structures of all but the smallest irrigation systems influence the equity of their shares in system benefits. In some areas of southern India, farmers at the head end of the system not only apply more water to their fields than necessary, but also interfere with the main canal system to maximize their supplies, thereby reducing the flow to farmers farther down the canal (Wade 1986). Where headenders need the capital and labor of tailenders, however, relatively more water reaches the tail of the system, while modernization of headworks often has the effect of decreasing the equity of water distribution because the contributions of tailenders are no longer needed for maintenance.

Ostrom (1993) has found that, in negotiations over the rules of water use between the members of a local water-user association, the bargaining power of tailenders is greater if their labor is needed to maintain the system. On the other hand, because the contributions of irrigators from all parts of the system are no longer needed, many successful farmer-organized water-user associations collapse soon after their systems have been "modernized" to decrease labor requirements and maintenance costs. In a comparison of 127 irrigation systems in Nepal, it was found that uneven distribution of water between head and tail ends was correlated with installation of permanent headworks in agency-managed systems, which no longer required the labor of tailenders to maintain (Ostrom, Benjamin, and Shivakoti 1992). During the wet season, adequate water reached the tail ends of only half of the agency-managed systems, compared to 90 percent of the farmer-managed systems. During the dry season this pattern was even stronger, with adequate water reaching the tail in only 8 percent of the modernized systems, compared to 25 percent of the traditional systems.[10]

In some cases, tail-to-head distribution of irrigation water leads to increased equity. Netherly (1987) has described the relative equity of the pre-Hispanic practice of tail-to-head distribution in Peru, compared to the less equitable system of upstream-user priority imposed during the Spanish colonial period. From his comparisons, Chambers (1984b) concludes that redistribution of some water from head to tail can potentially achieve several important objectives simultaneously, including increased equity.

> If less water is issued at the top, farmers there can grow crops that are more suitable for the soil, and if water is redistributed to the tails, then total production should rise, and equity will be served. Stability will be enhanced through reduced waterlogging. Carrying capacity will be increased through higher labor demand both in the head reaches . . . and in the tail where irrigated area and intensities increase. Well-being should gain through these effects, through reduced health hazards from standing water in the head reaches, and through more canal water for domestic purposes in the tails. (Chambers 1984b:37)

### Variability in Landholdings and Incomes

The gap between the largest and smallest landholders is frequently magnified by modernization, or industrialization, of irrigation, and this influences the distributions of water and incomes. In his comparison of the effects of introducing public-managed irrigation in two major irrigation projects in Maharashtra, India, Dhawan (1984) found that all farm incomes increased, but that income differences between large and small farmers also increased due to the former's better access to water, credit, and extension services. In public irrigation schemes in central Tunisia where water is often scarce and therefore costly, farmers who cannot afford irrigation either abandon it or greatly restrict its use, making more water available to the farmers who can afford it, whose yields and incomes thereby increase (Salem-Murdock 1990). A similar pattern has been documented in the Cape Verde Islands (Langworthy and Finan, chapter 8). Chambers (1984b:29) refers to comparative data from several parts of South and East Asia to suggest that "water distribution between farms tends to be more equitable the more equal the landholdings are, quite apart from the direct effect of the relative equality of the farm sizes."

### Loci of Resource Control

The locus of control of an irrigation system also affects the equitability of benefit distribution, as well as efficiency and stability. Whether crucial management decisions are in the jurisdiction of local farmers or distant bureaucrats seems to make a difference. Comparisons indicate that income variance among irrigators tends to be less in locally managed systems than in agency-managed ones, suggesting that there is an inverse correlation between centralized control and equity. In twenty-six different cases, Tang (1992) found that income variance was generally higher in agency-managed irrigation systems than in locally managed ones, although half of the community systems displayed moderate income variance among irrigators. Some of this variability, the data indicate, is related to the asymmetrical benefits accruing to headenders from construction of permanent headworks that increase total water delivery only to the top of canal distribution systems.

### Equity and Irrigated Agricultural Production

The patterns in the comparative data reviewed here support our hypothesis about equity in irrigated agriculture. The equitability of water allocation can be measured alternatively according to different, culturally defined principles of resource access and use. Among the factors that affect equitability in most irrigation systems are the rules specifying the relationship between contributions and benefits, the relative structural positions of irrigators, variance in landholdings and incomes, and the loci of resource control. Indigenous irrigation systems should not, however, be overly romanticized or intellectualized as ideally egalitarian. Traditional irrigation communities and water-user associations are not representative of Wittfogel's "hydraulic despotism"—they are usually small, simple, and decentralized. They are also not examples of Marx's "primitive communes"—risks are spread evenly through the group, not surpluses or profits. In terms of decision making, irrigation communities and water-user associations may be natural loci of "agrarian democracy" (Netting 1989), but they are not necessarily the egalitarian "village republics" envisioned by some (Wade 1988). Comparisons show that they tend to be internally egalitarian but exclusionary, and previous local inequalities may be reinforced by the marginalization of the less powerful during the process of development.

## The Relative Substitutability of Indigenous and Industrial Irrigation

We conclude that the data we have reviewed support acceptance of a number of hypothetical comparisons between indigenous and industrial irrigation based on the theory that indigenous modes of irrigated agriculture tend to be more sustainable (table 11.2). In general, indigenous systems use energy and natural resources more efficiently, have lower but more stable yields, and are more equitable in the distribution of opportunities, benefits, and risks. A capital- and energy-intensive system of irri-

**Table 11.2** Hypothetical comparisons between indigenous and industrial agriculture, based on the theory that indigenous systems are more sustainable.

| System level | Indigenous | Industrial |
|---|---|---|
| **Crops** | | |
| Number and types of varieties | More folk varieties (FVs)[a] | More modern varieties (MVs)[b] |
| Genetic diversity | Higher | Lower |
| Yield under marginal conditions | Higher | Lower |
| Yield under optimal conditions | Lower | Higher |
| Yield stability | Higher | Lower |
| **Farms, fields** | | |
| Number of crop species, varieties | Higher | Lower |
| Diversity of environments | Higher | Lower |
| Size | Smaller | Larger |
| Outside inputs | Lower | Higher |
| Specialization | Lower | Higher |
| Farmer risk | Lower | Higher |
| **Region** | | |
| Number of fields, crop systems | Larger | Smaller |
| Outside inputs | Lower | Higher |
| Synchrony of yields | Lower | Higher |
| **Irrigation system** | | |
| Cropping intensity | Lower | Higher |
| Water sources | Local, many | Central, few |
| Control of water distribution | Local | Central |
| Water consumption of crops | Lower | Higher |
| Risk of waterlogging, salinization | Lower | Higher |
| **Whole system** | | |
| Proportion of NPP[c] used | Lower | Higher |
| Social organization | Local community | Hierarchical bureaucracy |

**Table 11.2** (*continued*)

| System level | Indigenous | Industrial |
|---|---|---|
| Equity | Higher | Lower |
| Energy efficiency | Higher | Lower |
| Diversity | Higher | Lower |
| Stability | Higher | Lower |

*Source:* Adapted from Cleveland 1995

*a.* Also called "farmers' varieties," "traditional varieties," "landraces"

*b.* Also called "high-yielding varieties" (HYVS)

*c.* "Net primary product" of plant photosynthesis

gated agriculture may be able to sustain considerable levels of population by raising yields, but the productive resource base may be degrading. The apparently high levels of efficiency, stability, and equity of industrial irrigation, in reality based on external inputs and central management, may over the long term, be low relative to indigenous irrigation systems that must rely solely on local resources of labor, land, and leadership.

To accurately model the sustainability of an agroecosystem, calculations of efficiency must include the costs of capital, energy, and water subsidies, and also the contributions of forms of capital other than human-made. In the accounting, subsidizing and future discounting of natural capital should be replaced by its adequate valuation, and calculation of its depreciation (Norgaard and Howarth 1991; El Serafy 1991). Ecosystem complexity and genetic diversity should be included in this category, along with ecosystem regenerative and assimilative capacities. The concept of capital, even if restricted to the neoclassical sense of the economy's stock of real goods that are capable of producing further goods and utilities, should also be extended to include human organizational capacities such as social capital (Coleman 1988). Examples include those institutions in local irrigation organizations that facilitate sustainable resource management, equitable allocation, and stable production by providing collective-action mechanisms for rule-making, compliance-monitoring, conflict resolution, decision enforcement, and rule formulation and modification (Ostrom 1993; Mabry, chapter 1).

Even with these adjustments, however, the neoclassical economic model may be of limited applicability to agriculture, including irrigation. It has been said that "rivers express a rationality different from economics" (Worster 1984:58). The same can be said of traditional, subsistence-oriented systems of irrigated agriculture, which often function in contexts not dominated by market economic forces, and which measure efficiency in terms other than productivity and profit.

Although the data reviewed here offer some support for our hypothesis, our comparisons between indigenous and industrial systems of irrigation agriculture summarize only a few of the complex relationships between the many variables involved in agricultural production, and the results may often depend on the specific sets of cases considered. There is certainly much more to learn, and new data must be collected to test these hypotheses based on the theory of the greater sustainability of indigenous types of agriculture. At the very least, a transformation in how we think about and measure the properties that determine agricultural sustainability is necessary to help redirect irrigation development—a change in course demanded by ecological, economic, and demographic realities.

Because lending for water development projects by international donors has declined by more than 60 percent in the last decade (Postel 1989) as world population has continued to explode, governments in the developing world will be forced to shift their efforts to rehabilitating indigenous irrigation systems to grow food crops, rather than replacing them with expensive, complicated foreign water control technologies to boost cash crop production for distant markets (Coward and Levine 1989). The result of this shift in technology and management may be a "water revolution" that will stabilize food production and deliver benefits to the least-advantaged farmers (Chambers 1980; Freeman 1989). It will most likely be driven by a synthesis of indigenous knowledge and industrial technology, but based on values and goals more similar to those of indigenous than industrial systems of agriculture.

The critical obstacles are, inescapably, the high rate of resource consumption by a relatively small proportion of the global population and the high rate of world population growth. Development of sustainable agriculture may only be possible with a smaller number of people who consume, on average, fewer resources. The final choice among systems of intensive food production may be between a monolithic, industrial irrigated agriculture that can support a large and growing population for only a short time, or a diversity of locally adapted systems of irrigated agriculture, based on indigenous knowledge, that can sustain smaller, stable populations over the long run. In the words of farmer-poet Wendell Berry, after seeing the vast differences between traditional and industrial types of irrigated agriculture in the southwestern United States, "It is better to sustain a small population indefinitely than to build up a large artificial population on an agricultural system of which the basic principle is a willingness to destroy itself" (Berry 1981:67).

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## Notes

1. If energy is considered an equally significant factor of production, one of the clearest trends in the industrialization of agriculture is the substitution, for labor and land, of human-made capital (in the forms of machinery, scientifically bred seeds, and infrastructures like barns, silos, greenhouses, and irrigation systems) and energy (in the forms of electricity and fossil fuels for tractors, pumps, and other machinery, and also agrochemicals derived from fossil fuels). In the nineteenth century, capital inputs were emphasized in North America because of the relatively abundant land, large farms, and limited labor supply, while energy inputs were more important in Europe where land was scarcer and labor more plentiful (Dahlberg 1990). Energy use in agriculture has increased in both regions since World War II, with the fastest rates of substitution of fossil fuel for human labor in the United States and the United Kingdom (Stanhill 1984). This same trend has occurred in irrigation at a global scale, as increased use of pumps powered by fossil fuels has accompanied the spread of industrial irrigation. Between 1950 and 1985, as total energy use in agriculture increased about 700 percent, fuel use in irrigation increased 1200 percent (Albertson and Bouwer 1992).

2. Scaling of energy inputs and outputs to the number of acres harvested reveals that output per acre steadily declined relative to energy use per acre between 1910 and 1974 (C. Cleveland 1991). This long downward trend in energy efficiency was caused by accelerating use of petroleum and petroleum-derived agrochemicals. The recent upward trend is due to sharply declining use of agrochemicals after the energy price shocks of 1973–1974 and 1980–1981, and also the removal of marginal, lower-quality land from production under government-subsidized land conservation and price stabilization programs, thereby increasing the average yield per acre.

3. In reality, these ratios are probably even higher where draft animals are grazed on post-harvest stubble and natural pasture; animal labor inputs are based on energy outputs that are otherwise partially lost, or that are external to the cropping system.

4. Studies of irrigated agriculture in industrialized and developing regions have also shown that greater numbers of small holdings on the same amount of land provide more livelihoods per unit of water, thus improving rural quality of life (Goldschmidt 1978; Chambers 1984a).

5. A central component of agricultural stability is yield stability, or "the relatively constant annual yield of a crop grown by a farmer," and is "one of the most important issues facing world agriculture and food production; in some cases, stability is equally as important as yield itself" (Federer and Scully 1993:612). We define yield stability as a measure of variability of yield through time or across space, measured by variance (absolute stability) or the coefficient of variation (relative stability) (see Cleveland 1993).

6. Although the overall trend of increasing instability does appear to be accepted by most researchers, there are certainly many exceptions, and conclusions depend on research designs (e.g., Singh and Byerlee 1990).

7. The methodological difficulties of measuring the relationship between irrigation intensity and variability in production are pointed out in Dhawan's (1988:72–73) critique of Hazell's (1982, 1984) finding of a rise from 3.16 to 14.10 percent in the coefficient of variation for food grains in Tamil Nadu state between pre- and post-Green Revolution periods—an increase of 346 percent. By adding some food grains not included in Hazell's calculations, as well as all other crop output, and replacing two drought years during the pre-Green Revolution period that Hazell had removed because "catastrophes of this kind are sufficiently rare and severe . . . that they can be considered as separated phenomena from the more usual year-to-year fluctuations" (Hazell 1982:13), Dhawan calculates coefficients of variation for the earlier (5.56 percent) and later (8.14 percent) periods that show a much smaller increase (1988:72). Contradicting our hypothesis, Dhawan (1988:173) also found that, for most states in India, the coefficient of variation is smaller for irrigated than for nonirrigated production. But, unlike Hazell, Mehra, and others, he concentrates on differences between irrigated and nonirrigated areas for one period of time, and not on the changes accompanying the increase in irrigation and agricultural industrialization through time. Thus, important differences between irrigated and unirrigated areas directly related to irrigation—for example, that irrigation projects are usually sited on the best soils—are not controlled for.

8. Dhawan (1988:154–55) also discusses water source as another important factor in determining variability in the effects of irrigation, based on six years of crop production data from three districts in Tamil Nadu state in India. The coefficient of variation in yield for the district where canal irrigation predominates was 18 percent, while it was 26 percent in the state where hand-dug wells are the most important irrigation water source and 36 percent in the state where tank irrigation is most common.

9. It has been estimated that in the Third World by 1982–1983, 50.7 million hectares were planted in modern varieties of wheat and 72.6 million hectares were planted in modern varieties of rice, or 51.9 and 53.6 percent, respectively, of the total areas planted in those crops (Dalrymple 1986:85–86). Out of the total of 79.1 million hectares planted in maize in the Third World in 1985–1986, 51 percent (40 million hectares) were planted to modern varieties (38 percent in hybrids, and 13 percent in open-pollinated varieties) (Timothy, Harvey, and Dowsell 1988:53–55).

10. In practice, both headender and tailender priority rules are common, as well as

modified and combined versions of these rules (Ostrom 1993). In some systems, for example, a rotation system starts at the head one year, and at the tail the next.

## References Cited

Albertson, Maurice L., and Herman Bouwer

1992 Future of Irrigation in Balanced Third World Development. *Agricultural Water Management* 21:33–44.

Alvares, Claude, and Ramesh Billorey

1988 *Damming the Narmada: India's Greatest Planned Environmental Disaster.* San Francisco: Third World Network/Asia-Pacific People's Environmental Network.

Anderson, Jock R., and Peter B. R. Hazell

1989 Introduction. In *Variability in Grain Yields: Implications for Agricultural Research and Policy in Developing Countries,* ed. J. R. Anderson and P. B. R. Hazell, 1–10. Baltimore: Johns Hopkins University Press.

Barker, Randolph, Eric C. Gabler, and Donald Winkelmann

1981 Long-Term Consequences of Technological Change on Crop Yield Stability: The Case for Cereal Grain. In *Food Security for Developing Countries,* ed. A. Valdés, 53–78. Boulder, Colo.: Westview Press.

Barker, Randolph, and Robert W. Herdt, with Beth Rose

1985 *The Rice Economy of Asia.* Washington, D.C.: Resources for the Future.

Barlett, Peggy F.

1989 Industrial Agriculture. In *Economic Anthropology,* ed. S. Plattner, 253–91. Stanford: Stanford University Press.

Batty, J. C., and J. Keller

1980 Energy Requirements for Irrigation. In *Handbook of Energy Utilization in Agriculture,* ed. D. Pimentel, 35–44. Boca Raton: CRC Press.

Berry, R. A., and W. R. Cline

1979 *Agrarian Structure and Productivity in Developing Countries.* Baltimore: Johns Hopkins University Press.

Berry, Wendell

1981 Three Ways of Farming in the Southwest. In *The Gift of Good Land: Further Essays Cultural and Agricultural,* by W. Berry, 47–76. San Francisco: North Point Press.

Brown, Lester R., and John E. Young

1990 Feeding the World in the Nineties. In *State of the World 1990: A Worldwatch Institute Report on Progress Toward a Sustainable Society,* 59–78. New York: W. W. Norton.

Byerlee, Derek

1990 Technological Challenges in Asian Agriculture in the 1990s. In *Agricultural Development in the Third World,* 2nd edition, ed. C. K. Eicher and J. M. Staatz, 424–33. Baltimore: Johns Hopkins University Press.

Chambers, Robert

1980 In Search of a Water Revolution: Questions for Managing Canal Irrigation in the 1980s. In *Irrigation Water Management,* 23–37. Las Banos, Philippines: International Rice Research Institute.

1984a Beyond the Green Revolution: A Selective Essay. In *Understanding Green Revolutions: Agrarian Change and Development Planning in South Asia,* ed. T. P. Bayless-Smith and S. Wanmali, 362–79. Cambridge: Cambridge University Press.

1984b Irrigation Management: Ends, Means and Opportunities. In *Productivity and Equity in Irrigation Systems,* ed. N. Pant, 13–50. New Delhi: Ashish.

1988 *Managing Canal Irrigation: Practical Analysis from South Asia.* Cambridge: Cambridge University Press.

Chibnik, Michael

1990 Double-Edged Risks and Uncertainties: Choices About Rice Loans in the Peruvian Amazon. In *Risk and Uncertainty in Tribal and Peasant Economies,* ed. E. Cashdan, 279–302. Boulder, Colo.: Westview Press.

Cleveland, Cutler J.

1991 Natural Resource Scarcity and Economic Growth Revisited: Economic and Biophysical Perspectives. In *Ecological Economics: The Science and Management of Sustainability,* ed. R. Costanza, 289–317. New York: Columbia University Press.

Cleveland, David A.

1990 Development Alternatives and the African Food Crisis. In *Confronting Change. Stress and Coping in African Food Systems,* Vol. 2, ed. R. Huss-Ashmore and S. Katz, 181–206. New York: Gordon and Breach.

1993 Is Diversity More than the Spice of Life? Diversity, Stability, and Sustainable Agriculture. *Culture and Agriculture* 45–46:2–7.

1995 Diversity, Stability, and Sustainable Agriculture. Unpublished manuscript in possession of author.

1996 Are Large Scale Irrigation Projects Sustainable? The Case of Swabi SCARP, Pakistan. Manuscript under review.

Cleveland, David A., Daniela Soleri, and Steven E. Smith

1994 Do Folk Crop Varieties Have a Role in Sustainable Agriculture? *Bioscience* 44(11)740–51.

Coleman, James

1988 Social Capital in the Creation of Human Capital. *American Journal of Sociology* 91(1):309–35.

Coward, E. Walter, Jr., and Gilbert Levine

1989 Studies of Farmer-managed Irrigation Systems: Ten Years of Cumulative Knowledge and Changing Research Priorities. In *Public Intervention in Farmer-Managed Irrigation Systems,* 1–31. Publication No. 4. Sri Lanka: International Irrigation Management Institute.

Cox, George W., and Michael D. Atkins

1979 *Agricultural Ecology: An Analysis of World Food Production Systems.* San Francisco: W. H. Freeman.

Dahlberg, Kenneth A.

1990 The Industrial Model and Its Impacts on Small Farmers: The Green Revolution as a Case. In *Agroecology and Small Farm Development,* ed. M. A. Altieri and S. B. Hecht, 83–90. Boca Raton: CRC Press.

Dalrymple, Dana G.

1986 *Development and Spread of High-Yielding Wheat Varieties in Developing Countries.* Washington, D.C.: Bureau for Science and Technology, United States Agency for International Development.

Daly, Herman E.

1990 Toward Some Operational Principles of Sustainable Development. *Ecological Economics* 2:1–6.

Daly, Herman E., and John B. Cobb, Jr.

1989 *For the Common Good: Redirecting the Economy Toward Community, the Environment, and a Sustainable Future.* Boston: Beacon Press.

Dhawan, B. D.

1984 Differential Income Impact of Public Canal Irrigation in Maharashtra. In *Productivity and Equity in Irrigation Systems,* ed. N. Pant, 125–45. New Delhi: Ashish.

1988 *Irrigation in India's Agricultural Development: Productivity, Stability, Equity.* New Delhi: Sage Press.

Dover, Michael J.

1985 *A Better Mousetrap: Improving Pest Management for Agriculture.* Washington, D.C.: World Resources Institute.

El Serafy, Salah

1991 The Environment as Capital. In *Ecological Economics: The Science and Management of Sustainability,* ed. R. Costanza, 168–75. New York: Columbia University Press.

Federer, W. T., and B. T. Scully

1993 A Parsimonious Statistical Design and Breeding Procedure for Evaluating and Selecting Desirable Characteristics Over Environments. *Theoretical and Applied Genetics* 86:612–20.

Food and Agriculture Organization

1991 *Production Yearbook 1990,* Vol. 44. Rome: United Nations.

Freeman, David M.

1989 *Local Organizations for Social Development: Concepts and Cases of Irrigation Organization.* Boulder, Colo.: Westview Press.

Gazdar, Muhammad Nasir

1990 *An Assessment of the Kalabagh Dam Project on the River Indus in Pakistan. The Sabz Bagh: "Promising a Rose Garden but Delivering Dust."* Karachi, Pakistan: Environmental Management Society, Pakistan Environmental Network.

Geertz, Clifford

1963 *Agricultural Involution: The Process of Ecological Change in Indonesia.* Berkeley: University of California Press.

Goldschmidt, Walter

1978 *As You Sow: Three Studies in the Social Consequences of Agribusiness.* Montclair, N.J.: Allenheld, Osmun and Company.

Hazell, Peter B. R.

1982 *Instability in Indian Foodgrain Production.* Research Report 30. Washington, D.C.: International Food Policy Research Institute (IFPRI).

1984 Sources of Increased Instability in Indian and U.S. Cereal Production. *American Journal of Agricultural Economics* 66:302–11.

1989 Changing Patterns of Variability in World Cereal Production. In *Variability in Grain Yields: Implications for Agricultural Research and Policy in Developing Countries,* ed. J. R. Anderson and P. B. R. Hazell, 13–34. Baltimore: Johns Hopkins University Press.

Jodha, N. S.

1990 *Rural Common Property Resources: A Growing Crisis.* London: International Institute for Environment and Development (IIED).

Lynam, John K., John H. Sanders, and Stephen C. Mason

1986 Economic Risk in Multiple Cropping. In *Multiple Cropping Systems,* ed. C. Frances, 250–66. New York: Macmillan.

Mabry, Jonathan B., Hsain Ilahiane, and John R. Welch

1991 *Rapid Rural Appraisal of Moroccan Irrigation Systems: Methodological Lessons from the Pre-Sahara.* Report submitted to United States Agency for International Development, Morocco, Rabat.

Mandal, M. A. S.

1987 Development of Small-Scale Lift Irrigation in Bangladesh. In *Public Intervention in Farmer-Managed Irrigation Systems,* 131–47. Digana, Sri Lanka: International Irrigation Management Institute.

Mehra, Shakuntla

1981 *Instability in Indian Agriculture in the Context of the New Technology.* Research Report No. 25. Washington, D.C.: IFPRI.

Merrey, Douglas J.

1987 The Local Impact of Centralized Irrigation Control in Pakistan: A Sociocentric Perspective. In *Lands at Risk in the Third World: Local Level Perceptions,* ed. P. D. Little and M. Horowitz, 352–72. Boulder, Colo.: Westview Press.

Netherly, Patricia J.

1987 Hydraulics and the Organization of Irrigation in the High Civilizations of the Andean Region of South America. In *Water for the Future: Water Resources Developments in Perspective,* ed. W. O. Wunderlich and J. E. Prins, 153–61. Boston: A. A. Balkema.

Netting, Robert McC.

1989 Smallholders, Householders, Freeholders: Why the Family Farm Works Well Worldwide. In *The Household Economy: Reconsidering the Domestic Mode of Production,* ed. R. Wilk. Boulder, Colo.: Westview Press.

1993 *Smallholder, Householders: Farm Families and the Ecology of Intensive, Sustainable Agriculture.* Stanford: Stanford University Press.

Norgaard, Richard B., and Richard B. Howarth

1991 Sustainability and Discounting the Future. In *Ecological Economics: The Sci-*

*ence and Management of Sustainability,* ed. R. Costanza, 88–101. New York: Columbia University Press.

Oomen, J. M. V., J. deWolf, and W. R. Jobin

1988 *Health and Irrigation: Incorporation of Disease-Control Measures in Irrigation, a Multi-faceted Task in Design, Construction, and Operation.* Publication No. 45. Wageningen, Netherlands: International Institute for Land Reclamation and Improvement.

Ostrom, Elinor

1992 The Rudiments of a Theory of the Origins, Survival and Performance of Common Property Institutions. In *Making the Commons Work: Theory, Practice, and Policy,* ed. D. W. Bromley, 293–318. San Francisco: ICS Press.

1993 Constituting Social Capital and Collective Action. Paper presented at "Heterogeneity and Collective Action," Workshop in Political Theory and Policy Analysis, Indiana University, Bloomington.

Ostrom, Elinor, Paul Benjamin, and Ganesh Shivakoti

1992 *Institutions, Incentives, and Irrigation in Nepal,* Vol. 1, *Workshop in Political Theory and Policy Analysis.* Bloomington: Indiana University Press.

Pandey, Sushil

1989 Irrigation and Crop Yield Variability: A Review. In *Variability in Grain Yields: Implications for Agricultural Research and Policy in Developing Countries,* ed. J. R. Anderson and P. B. R. Hazell, 234–41. Baltimore: Johns Hopkins University Press.

Park, Thomas K.

1992 Early Trends Toward Class Stratification: Chaos, Common Property, and Flood Recession Agriculture. *American Anthropologist* 94(1):90–117.

Pimentel, David, and Marcia Pimentel

1979 *Food, Energy and Society.* London: Edward Arnold.

Postel, Sandra

1989 *Water for Agriculture: Facing the Limits.* Paper No. 93. Washington, D.C.: Worldwatch Institute.

1992 *Last Oasis: Facing Water Scarcity.* New York: W. W. Norton.

Qasem, Subhi

1990 Issues of Food Security in the Arab Countries. In *Agriculture in the Middle East: Challenges and Possibilities,* ed. A. Salman, 161–77. New York: Paragon House.

Repetto, Robert

1986 *Skimming the Water: Rent-Seeking and the Performance of Public Irrigation Systems.* Paper No. 4. Washington, D.C.: World Resources Institute.

Roberts, Edwin B., Richard H. Cuenca, and Robert M. Hagan

1986 Energy and Water Management with On-Farm Irrigation Systems. In *Energy and Water Management in Western Irrigated Agriculture,* ed. N. K. Whittlesey, 35–71. Boulder, Colo.: Westview Press.

Ryder, Gráinne

1988 China's Three Gorges Project: Whose Dam Business Is It? *Cultural Survival Quarterly* 12(2):17–19.

Ruttan, V. W.

1984 Induced Innovations and Agricultural Development. In *Agricultural Sustainability in a Changing World Order,* ed. G. K. Douglass, 107–34. Boulder, Colo.: Westview Press.

Sagardoy, J. A.

1982 *Organization, Operation and Maintenance of Irrigation Schemes.* Irrigation and Drainage Paper 40. Rome: Food and Agriculture Organization of the United Nations.

Saini, G. R.

1979 *Farm Size, Resource-use Efficiency and Income Distribution: A Study in Indian Agriculture, with Special Reference to Uttar Pradesh and Punjab.* Bombay: Allied Publishers.

Salem-Murdock, Muneera

1990 Household Production Organization and Differential Access to Resources in Central Tunisia. In *Anthropology and Development in North Africa and the Middle East,* ed. M. Salem-Murdock and M. M. Horowitz, with M. Sella, 95–125. Boulder, Colo.: Westview Press.

Sanders, William T., and Robert S. Santley

1983 A Tale of Three Cities: Energetics and Urbanization in Pre-Hispanic Central Mexico. In *Prehistoric Settlement Patterns: Essays in Honor of Gordon R. Willey,* ed. E. Vogt and R. Leventhal, 243–91. Albuquerque: University of New Mexico Press.

Scudder, Thayer

1989 Conservation vs. Development: River Basin Projects in Africa. *Environment* 31(2):4–9, 27–31.

Sheridan, David

1984 *Cropland or Wasteland: The Problems and Promises of Irrigation.* London: International Institute for Environment and Development.

Singh, A. J., and D. Byerlee

1990 Relative Variability in Wheat Yields across Countries and Over Time. *Journal of Agricultural Economics* 41:21–32.

Stanhill, G.

1984 Agricultural Labour: From Energy Source to Sink. In *Energy and Agriculture,* ed. G. Stanhill, 113–30. Berlin: Springer-Verlag.

Strange, Marty

1988 *Family Farming: A New Economic Vision.* Lincoln: University of Nebraska Press and San Francisco: Institute for Food and Development Policy.

Swearingen, Will D.

1987 *Moroccan Mirages: Agrarian Dreams and Deceptions, 1912–1986.* Princeton: Princeton University Press.

Tang, Shui Yan

1992 *Institutions for Collective Action: Self-Governance in Irrigation.* San Francisco: ICS Press.

Timothy, David H., Paul H. Harvey, and Christopher R. Dowsell
1988 *Development and Spread of Improved Maize Varieties and Hybrids in Developing Countries.* Bureau for Science and Technology, United States Agency for International Development, Washington, D.C.
Umali, Dina L.
1993 *Irrigation-Induced Salinity.* Technical Paper No. 215. Washington, D.C.: World Bank.
Uphoff, Norman, M. L. Wickramasinghe, and C. M. Wijayaratna
1990 "Optimum" Participation in Irrigation Management: Issues and Evidence from Sri Lanka. *Human Organization* 49(1):26–40.
Wade, Robert
1986 Common Property Resource Management in South Indian Villages. In *Common Property Resource Management,* 231–57. Washington, D.C.: National Research Council, National Academy of Sciences.
1988 *Village Republics: Economic Conditions for Collective Action in South India.* Cambridge University Press.
Walker, T. S.
1989 High Yielding Varieties and Variability in Sorghum and Pearl Millet Production in India. In *Variability in Grain Yields: Implications for Agricultural Research and Policy in Developing Countries,* ed. J. R. Anderson and P. B. R. Hazell, 91–99. Baltimore: Johns Hopkins University Press.
Wilk, Richard R.
1985 Dry Season Agriculture among the Kekchi Maya and Its Implications for Prehistory. In *Prehistoric Lowland Maya Environment and Subsistence Economy,* ed. M. Pohl, 47–57. Papers of the Peabody Museum of Archaeology and Ethnology, Vol. 77. Cambridge: Harvard University.
World Bank
1992 *World Development Report 1992: Development and the Environment.* Washington, D.C.: World Bank and Oxford University Press.
World Resources Institute
1990 *World Resources, 1990–91.* New York: Oxford University Press.
1992 *World Resources, 1992–93.* New York: Oxford University Press.
Worster, Donald
1984 Thinking Like A River. In *Meeting the Expectations of the Land: Essays in Sustainable Agriculture and Stewardship,* ed. W. Jackson, W. Berry, and B. Colman, 55–67. San Francisco: North Point Press.
1985 *Rivers of Empire: Water, Aridity and the Growth of the American West.* New York: Pantheon.
Yates, P.
1981 *Mexico's Agricultural Dilemma.* Tucson: University of Arizona Press.