DISCUSSION PAPER

WATER AND FERTILIZER USE IN SELECTED COUNTRIES

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

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Abstract

In many developing countries, food production growth rates are slipping behind population growth rates while some measures designed to increase output are degrading the resource base.

However, the appropriate use of inputs offers a viable path to achieving food security while safeguarding natural resources. In combination, relatively small applications of fertilizer and irrigation water can be particularly effective at boosting crop yields, improving rural incomes and supporting economic development.

Enhancing the availability of human and financial capital and enabling appropriate prices for agricultural inputs and outputs will encourage farmers to invest and be more productive. Hence, in order to develop valid methods for determining the appropriate water and fertilizer balance in different socio-economic and climate conditions in rainfed and irrigated areas, it is necessary to examine all relevant factors from government policy to pest control. Overcoming data constraints will facilitate progress in this field.

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List of acronyms

EC	Electrical conductivity
HYV	High-yielding variety
MPP	Marginal physical product
MVP	Marginal value product
NWFP	North-West Frontier Province
ORMVA	Office Régional de Mise en Valeur Agricole
TFP	Total factor productivity
TPP	Total physical product

Chapter 1
Introduction[1]

In the next 25 years the world will produce enough food to meet the demand of those people who can afford to buy it, and the forecast is for real food prices to continue their declining trend. However, the prospects for food security will be bleak for millions of people, and the degradation of natural resources will continue.

By 2030, global irrigated rice, wheat and maize production will be 70 percent higher than the 1995-97 level of 1 150 million tonnes. However, despite growing at an annual compounded rate of 1.6 percent, food production is unlikely to keep pace with rising demand in many developing countries. The gap between cereal production and demand could more than double in the next 30 years. In addition, changes in lifestyles and income levels may affect food security throughout the developing world. This is especially pertinent with regard to developments in China and India as together they account for nearly 40 percent of the world's population.

This report focuses on three selected sample countries (Morocco, Pakistan and the Syrian Arab Republic) where improving rural incomes and enhancing food security are policy goals. In these countries, large proportions of the population live in rural areas and many residents derive income from agricultural activities. If recent estimates of population growth rates prove correct, the populations of Pakistan and Syria will double within 27 years, while Morocco's population will double in 37 years. This momentum in population growth highlights the urgency of issues regarding agricultural productivity, food security and economic growth. An expanding population increases the pressure on the agriculture sector as it demands greater production from an increasingly constrained area subject to encroachment by urban and industrial centres.

To meet rising food demand, it is possible to increase supply by: (i) expanding the area of arable land; (ii) boosting agricultural yields; and (iii) increasing cropping intensity. However, there can be only a limited expansion in the physical area of land available for agriculture. In the past 30 years, more than three-quarters of the production growth has come from increases in yields. This is likely to be the case also in the future. Much of the extra production will come from irrigated land. Currently, some 30 percent of agricultural lands in the developing countries receive irrigation and contribute about 40 percent of their crop production. Between 1962 and 1996, the irrigated area in developing countries almost doubled. Most analysts expect the irrigated area to expand much more slowly in future. FAO expects the irrigated areas in 93 developing countries to expand by 0.6 percent per year between 1996 and 2030, for an overall increase of 23 percent. Additional production would come from increased yields and an increase in the effective harvested area. Both of these sources of increased production depend on water and fertilizer inputs.

Agriculture accounts for about 70 percent of the freshwater withdrawals in the world. Some experts see this as a main factor in increasing global water scarcity. An analysis of 93 developing countries indicates that irrigation water withdrawal in these countries will increase by 12 percent in the period 1996-2030. This increase is low compared with the projected growth in the harvested

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[1] This discussion paper is based on inputs from A. Arslan, N. Ahemad, T. van den Bergen, A. Bouaziz, J. Plummer, J. Poulisse and D. Wichelns.

area. Improvements in irrigation productivity should lead to concomitant reductions in irrigation water withdrawal. Changes in cropping patterns in some countries (mainly from rice to wheat production) will also play a part in reducing water withdrawal. The estimated irrigation water requirements for rice are twice those for wheat production. However, there is a serious lack of reliable data on effective irrigation productivity.

Fertilizer applications are most efficient where the soil moisture level is adequate. Under other conditions their use may be insufficient and result in suboptimal yields. Where applied inappropriately, additional nutrients may lead to water contamination and emissions to the environment. Indeed, although water and fertilizer are basic agricultural productivity inputs, their use is coming under increasing scrutiny because of growing water scarcity and pollution of the environment resulting from excessive applications and poor management.

Research has provided data on productivity under optimal conditions at experiment stations for various crop varieties. However, comprehensive and reliable figures from real farming situations are scarce in developing countries. Such figures are of particular importance as agriculture adjusts to the need for accurate levels of water and fertilizer inputs in line with current water and fertilizer policies. In close cooperation with other partners, FAO intends to define procedures and compile a relevant database on water and fertilizer use in representative irrigation and rainfed areas (where such figures are available). It will then assemble these in a form that will facilitate agricultural analysis, projections and planning.

A frequently cited example states that providing a minimum diet of 2 200 calories per day to an individual requires 200 kg of cereal equivalent per year. Adding to this diet 1 000 calories of animal origin, and assuming that the production of one animal calorie requires seven cereal calories, the diet boosted to 3 200 calories requires about 850 kg of cereal equivalent. The production of 850 kg of cereal equivalent requires about 1 000 m^3 of water, and the crop requires an adequate application of fertilizer. Each of these figures calls for scrutiny and the definition of a range of variation. It is necessary to study: the amount of rainfall and irrigation water that serve as an input in typical agro-ecological regions; the amounts of water and fertilizer inputs required to achieve the observed yields under irrigated and rainfed conditions; the water and nutrient use efficiencies in typical irrigated or rainfed conditions; and the best way to quantify the scope for resource use productivity.

In view of the above considerations, this report focuses on the two productivity inputs which have the most significant impact on crop productivity: water and fertilizer. It endeavours to define the underlying factors determining water and fertilizer productivity under rainfed and irrigated management systems and to propose practical procedures for assessing water and fertilizer productivity from actual field data under various farm management and agro-ecological conditions. The study focuses on selected major crops (wheat, rice, maize, cotton, etc.) in the three sample countries and considers the process from the application of water and fertilizer through to harvest. The study seeks to establish a methodology for quantifying the volume of irrigation water and plant nutrients inputs required to support the yields obtained by farmers in different socio-economic and climate conditions in rainfed and irrigated areas. In addition, it examines other production parameters such as variables (pest control, etc.) and farming system constraints (labour, inputs, etc.). It reviews the relevant literature with a special focus on the three sample countries. It examines the relevant data and presents a comparative analysis of various methodologies and cases.

An important element in such a study should be the analysis of the effect of output and the income it generates on resource use. However, farmers often operate in conditions where output prices fail to reflect market values. This situation arises because of distortions caused by factors such as government intervention (e.g. support prices and price restrictions). Hence, their decisions about input use may be rational in their particular context but suboptimal in terms of appropriate, sustainable resource use. In addition, the lack of concrete, comparable data on such aspects is a significant constraint on attempts to validate theoretical models and to develop recommendations for widespread application.

Chapter 2

Means of intensification

OVERVIEW OF SAMPLE COUNTRIES

The agroclimatic characteristics of an area determine its crop production potential. However, actual agricultural production levels depend in particular on the use of two main inputs: irrigation and fertilizer, and on other inputs such as labour, high-yielding varieties (HYVs) and pesticides. The inputs do not act in isolation, they are interdependent. Indeed, the dynamics of various inputs determine the potential use of a particular input by the crop. For example, a water-stressed crop cannot use the nitrogen applied to its full potential (Rosenzweig and Iglesias, 1994 and 2001).

In the three countries which form the focus of this report (Pakistan, the Syrian Arab Republic and Morocco), the average productivity of land and water resources varies with the degree of irrigation development. Much of Pakistan's agricultural output comes the Indus River basin, where farmers divert surface water from an extensive canal system and where they obtain groundwater from private and public tubewells. The average yields of grains, sugar crops and cotton are much higher in irrigated areas than in rainfed zones. Most of the grain producing areas in Syria and Morocco do not receive irrigation. As a result, average yields are smaller and more variable than those in Pakistan.

The incremental values of inputs such as fertilizer and the seeds of HYVs are generally higher in irrigated areas than in rainfed zones, where expected yields are smaller and where uncertainty regarding rainfall events increases the risk of using fertilizer inputs. Hence, average use rate of fertilizers is higher in Pakistan than in Syria or Morocco. This higher use rate contributes to the higher average yields observed in Pakistan.

IRRIGATION AND FERTILIZER USE

At present there are an estimated 18 million ha of irrigated cropland in Pakistan, where the total arable and permanent cropland area is about 22 million ha. An estimated 1.2 million ha of Syria's 5.5 million ha of arable and permanent cropland area receive irrigation, while in Morocco the corresponding figure is 1.3 million ha out of a total cropland area of 9.44 million ha. The proportion of irrigated arable and permanent cropland is much higher in Pakistan (82 percent) than in Syria and Morocco (22 and 14 percent). Irrigated area increased slowly but steadily in Pakistan and Morocco from 1961 to 1980 while in Syria the irrigated area did not increase between 1962 and 1988. Since 1980, the irrigated areas in Pakistan and Morocco have increased only slightly, while the area irrigated in Syria has doubled. The rapid increase in Syrian irrigation since 1990 reflects that nation's effort to stimulate agricultural production in a larger portion of the Euphrates River basin.

TABLE 1
Fertilizer consumption in Pakistan, Syria and Morocco, 1999

Items	**Pakistan**	**Syria**	**Morocco**
Fertilizer consumption	(tonnes)		
Nitrogen fertilizers	2 210 800	251 202	168 900
Phosphate fertilizers	595 800	111 861	102 000
Potash fertilizers	17 700	8 256	56 900
Total fertilizers	2 824 300	371 319	327 800
Average (total consumption/ arable and permanent cropland area) (tonnes/ha)	129	68	35

Source: FAO data, available at www.fao.org.

In 1999, fertilizer use exceeded 2.8 million tonnes in Pakistan, compared with 371 000 tonnes in Syria and 328 000 tonnes in Morocco. In all three countries, nitrogen fertilizers accounted for more than half of the fertilizer applied in 1999. Data describing average fertilizer use rates on irrigated and non-irrigated land are not available. However, it is possible to estimate average fertilizer use in the three countries by dividing total fertilizer use by the arable and permanent cropland area (Table 1).

Fertilizer use has increased by a factor of more than 60 in Pakistan since 1962, while increasing by a factor of about 30 in Syria and by a factor of less than 10 in Morocco. The lower growth rates in Syria and Morocco reflect the smaller returns to fertilizer use on the rainfed lands that account for most of the agricultural area in those countries. Since 1980, fertilizer use has increased at a slightly faster pace in Syria than in Pakistan, as the irrigated area in Syria has increased substantially. Fertilizer use in Morocco has remained relatively constant since 1985.

Morocco

Recent persistent drought conditions have demonstrated the variability and uncertainty that characterize agricultural production in Morocco. Between 1995 and 2000 seasonal rainfall variations caused annual cereal production in Morocco to fluctuate between 18.5 and 139 percent of the cereal crop obtained in the period from 1989 to 1991. Cereal production in 2000 was 25 percent of the 1989-1991 average, causing an increase in cereal imports to 5.2 million tonnes (EIU, 2001c). About half of the cultivated land (barley/fallow rotation) receives no more than 350 mm of rainfall each year (Shroyer *et al*., 1990). Agricultural practices in rainfed areas are largely traditional, with limited use of fertilizer, pesticides, HYVs and machinery.

The average productivity of the 7 percent of the cereal-producing area in Morocco that does receive irrigation (FAO, 2001c) is substantially higher than rainfed land, particularly in years when rainfall is minimal. For example, the average yields of bread wheat, durum wheat and barley on irrigated lands were 30-60 percent higher than average yields on rainfed lands under the normal rainfall conditions between 1976 and 1979 (Table 2). By contrast, irrigated grain yields were three to four times greater than rainfed yields during the severe drought that lasted from 1980 to 1984. The average yield of irrigated bread wheat increased from 1.9 tonnes/ha in 1976-79 to 2.3 tonnes/ha in 1980-84 (a period when the area irrigated increased by 63 percent), while the average yield of rainfed bread wheat declined from 1.4 to 0.6 tonnes/ha. In 1980-84, the 29 percent of bread wheat area that received irrigation generated 62 percent of Morocco's bread wheat production.

The use of fertilizers in Morocco's agriculture sector rose steadily from 1965 to 1985 when fertilizer use reached a plateau of about 320 000 tonnes per year. Although much of the increase in fertilizer use has probably occurred in rainfed areas, the intensity of input use is probably

TABLE 2

Area, yield and total production of irrigated and rainfed cereals in Morocco, 1976-1984

	Area (ha)	**Irrigated yield** (kg/ha)	**Production** (tonnes)	**Area** (ha)	**Rainfed yield** (kg/ha)	**Production** (tonnes)
Cereal						
Bread wheat						
1976-79	60 500	1.9	117 000	158 000	1.4	215 000
1980-84	98 600	2.3	231 000	240 000	0.6	141 000
Durum wheat						
1976-79	67 500	1.7	118 000	2 460 000	1.3	3 007 000
1980-1984	54 100	1.8	97 000	2 550 000	0.6	1 430 000
Barley						
1976-79	65 600	1.6	102 000	2 075 000	1.0	2 120 000
1980-84	48 000	1.5	75 000	2 814 000	0.5	1 390 000
All grains						
1976-79	211 000	1.7	361 000	6 707 000	1.2	7 840 000
1980-84	222 000	2.0	441 000	8 424 000	0.5	4 530 000

Source: Shroyer *et al.*, 1990.

TABLE 3

Nutrient use in rainfed and irrigated agriculture in Morocco

Type of area	**Size of area** (million ha)	**Supplemental nutrients** **Nitrogen**	 **Phosphorous** (million tonnes)	 **Potash**	**Sum of nutrients** (million tonnes)	**Average application** (kg/ha)
Rainfed	8.1	74	43	22	139	17
Irrigated	1.1	102	59	31	192	175
Total	9.2	176	102	53	331	36

Source: FAO, 2001c.

greater on irrigated lands. Recent data (FAO, 2001c) suggest that the average application rates of fertilizer in Morocco are 17 kg/ha on rainfed lands and 175 kg/ha on irrigated lands (Table 3). Hence, the average productivity of irrigated lands is substantially higher than that of rainfed lands. In aggregate, about 45-50 percent of fertilizer consumption occurs on irrigated farms, while 35-40 percent occurs in the high rainfall zone and 15-20 percent occurs in the low and medium rainfall zones (Tuluy and Salinger, 1991). An estimated 16 percent of the surface area of farms smaller than 5 ha receives fertilizer, compared with 64 percent on farms that are 50-100 ha in size.

Pakistan

Value added in the agriculture sector of Pakistan has grown by a factor of four since 1950, but annual growth rates in crop production have fluctuated substantially. Growth rates in crop production grew from less than 2 percent per year in the 1950s to as high as 8.18 percent in the 1960s (Table 4). Much of the gain in the 1960s was due to improvements in productivity per hectare made possible by the adoption of higher yielding varieties of wheat and rice and rapid increases in the use of fertilizer and irrigation water (Ahmed, 1987; Chaudhry *et al.,* 1996). There were sustained gains in productivity per hectare of about 2.5 percent per year from the late 1970s to the early 1990s, while the average increase in cropland area fluctuated between 0.15 and 1.58 percent per year. The rate of growth in aggregate inputs has exceeded the rate of growth in crop production during two of the five most recent five-year periods shown in Table 4.

TABLE 4

Agricultural input, output and total factor productivity growth in Pakistan, 1950-1995

Period	Crop production	Cropland	Productivity per hectare (% per year)	Aggregate inputs	Total factor productivity
1950-55	0.33	1.24	-0.91	1.64	-1.31
1955-60	1.91	2.05	-0.14	2.40	-0.49
1960-65	4.74	2.03	2.73	2.30	2.56
1965-70	8.18	0.63	7.55	2.26	5.82
1970-75	0.48	0.70	-0.22	2.59	-2.11
1975-80	4.15	1.58	2.57	3.16	0.99
1980-85	2.63	0.15	2.48	3.32	-0.69
1985-90	3.70	1.50	2.10	2.83	0.87
1990-95	3.17	0.62	2.55	1.70	1.47
1949-95	3.02	1.31	1.71	2.54	0.48

Sources: Government of Pakistan, 1990, 1996; and Kemal and Ahmad, 1992, as reported in Chaudhry *et al.*, 1996.

The rate of growth in total factor productivity (TFP) has been negative or less than 1.5 percent in all periods since 1970. An examination of data describing the average productivity of land, water and fertilizer during the 1980s and 1990s can yield insights into the causes of declining growth rates in crop yields in Pakistan.

Fertilizer use has increased substantially on wheat-rice and wheat-cotton rotations and throughout Punjab, Pakistan, while the proportion of area irrigated and the cropping intensity have also increased (Table 5). Water use has increased on the wheat-rice rotation, but not on the wheat-cotton rotation. The wheat-rice rotation uses a larger volume of water from tubewells, while the wheat-cotton rotation uses a greater amount of canal water. In general, the use of tubewell water has increased over time, while canal water use has declined. For the whole of Punjab, the proportion of water provided by tubewells has increased from 23 percent in the green revolution period to 43 percent in the post-green revolution period.

The limited volume of water available in canals and the inherent rigidity of Pakistan's rotational irrigation system have motivated farmers to install private tubewells. Credit subsidies and flat-rate pricing of electricity beginning in the 1960s enhanced the pace of installation. By the early 1980s, there were 182 000 tubewells in Punjab, 19 300 in Sindh, 7 850 in Balochistan and 5 400 in North-West Frontier Province (NWFP) (Chaudhry, 1990). By the late 1980s private tubewells supplied more than 30 percent of farmgate available water in Pakistan (Mustafa and Pingali, 1995). By the mid-1990s more than 300 000 private tubewells were supplying about 40 percent of total irrigation water in Pakistan (Ahmad and Faruqee, 1999). Tubewells enhance agricultural production and land quality in regions where shallow groundwater is not saline, but they contribute to salinization in regions with brackish shallow groundwater (Faruqee, 1996). The extensive use of tubewells has enabled farmers in Punjab to increase the cropping intensities of cotton-wheat and rice-wheat rotations from about 100 percent in 1960 to about 150 percent in 1990.

The rates of yield increase in areas cropped and irrigated have declined in recent decades in Pakistan. In particular, for the areas cultivated, cropped and irrigated in Pakistan, yields increased by 23, 31 and 42 percent respectively between 1960 and 1980. From 1980 to 1999, the yield increases in these areas were 7, 19 and 22 percent respectively. Both cropping intensity and irrigation intensity have increased since the late 1970s, reaching values of 105 and 82 percent respectively in 1998-99. The declining rates of growth in both average productivity and cultivated area contribute to the declining rate of growth in total food grain production. Given that limited

TABLE 5

Input use in Punjab, Pakistan, 1966-1994

Crop rotation and input	**Green revolution (1966-1974)**	**Intensification (1975-1984)**	**Post-green revolution (1985-1994)**
Wheat-rice			
Fertilizer (kg/ha)	12	45	65
Water (1 000 m^3/ha)			
Tubewell	3 455	6 170	7 404
Canal	3 208	3 085	2 591
Sum	6 663	9 255	9 995
Irrigated area (%)	74	85	89
Crop intensity (%)	132	139	147
Wheat-cotton			
Fertilizer (kg/ha)	18	62	120
Water (1 000 m^3/ha)			
Tubewell	1 851	2 962	3 208
Canal	7 281	6 664	5 923
Sum	9 132	9 626	9 131
Irrigated area (%)	97	98	98
Crop intensity (%)	121	128	147
All Punjab			
Fertilizer (kg/ha)	14	48	86
Water (1 000 m^3/ha)			
Tubewell	1 728	3 085	3 702
Canal	5 800	5 306	4 813
Sum	7 528	8 391	8 515
Irrigated area (%)	82	85	86
Crop intensity (%)	117	126	136

Source: Ali and Byerlee, 1999.

water supplies will be a constraint on increases in cultivated and irrigated areas, efforts to boost productivity growth will be necessary in order to maintain growth in total food production. Substantial public investment enabled the improvements in crop yields and the increases in cropping and irrigation intensities of the 1960s and 1970s. Private investments in large-scale and small-scale irrigation facilities, improved seeds, mechanization and subsidized prices for water, energy and fertilizer also contributed significantly to these gains. Average water availability increased by 34 percent from 4 700 m^3/ha in 1959-60 to 6 300 m^3/ha in 1980-81 as a result of the completion of several large reservoirs and the widespread installation of public and private tubewells (Table 6). The average area served per tubewell declined from 3 066 ha in 1959-60 to 97 ha in 1980-81. The use of improved seeds increased by a factor of 2.63 between 1980-81 and 1996-97, while aggregate fertilizer use increased by 97 percent during that time to an average of 110 kg/ha. These rates of increase in the use of key inputs are substantially higher than the observed rates of increase in average crop yields in the 1980s and 1990s, suggesting that TFP declined in that period. Closer examination of crop production and input use in these decades could provide a better understanding of factors that may have contributed to the declining productivity of land, water and fertilizer inputs.

The aggregate amount of fertilizer used in agriculture have increased more rapidly than irrigated area since 1980-81. Total fertilizer consumption increased by a factor of about 2.5 during that time. At province level, nitrogen fertilizer consumption increased most rapidly in Punjab, rising by a factor of more than 2.5 in the period. Nitrogen use doubled in both Sindh and NWFP in this period. Phosphate fertilizer consumption doubled in Punjab and NWFP, while rising by

TABLE 6

Input use in Pakistan, 1950-51 to 1996-97

Year	Water availability (m^3/ha)	Improved seeds (kg/ha)	Fertilizer (NPK) (kg/ha)	Tubewells (ha/well)	Tractors (ha/unit)	Workers (ha/unit)
1950-51	3 950					2.16
1954-55	4 200		1.1	10 215	30 389	2.10
1959-60	4 700		1.3	3 066	4 088	1.88
1964-65	4 900		5.4	481	1 290	1.66
1969-70	5 550	1.2	18.3	196	633	1.62
1974-75	6 300	1.5	24.4	114	459	1.55
1980-81	6 300	3.8	55.8	97	202	1.50
1984-85	6 400	4.3	62.9	80	149	1.50
1989-90	6 800	2.9	86.3	66	138	1.40
1994-95	7 300	9.3	99.3	52	110	1.39
1996-97	7 400	10.0	110.0	47	70	1.38

Sources: Khan, 1997.

a factor of 1.8 in Sindh. Phosphate fertilizer consumption has been more variable than nitrogen consumption in recent years. Punjab accounts for 67 percent of the nitrogen fertilizer and 68 percent of the phosphate fertilizer consumed in Pakistan.

The amount of water available for irrigation will limit further increases in cropland area in Pakistan. Hence, future gains in agricultural production will require improvements in the average productivity of land and water resources within the Indus River basin and in rainfed areas outside the basin. Such improvements will require substantial efforts to restore the rates of growth in crop yields achieved in the 1960s and 1970s, particularly with respect to rice and wheat. The declining growth rates observed since 1980 are in part the consequence of the degradation of land and water resources caused by the inappropriate management of resources on farms and throughout irrigated areas (Mustafa and Pingali, 1995; Pingali and Shah, 1999; Murgai *et al.,* 2001). Repairing the damage caused by waterlogging, salinization and poor management of soil fertility will be expensive and time consuming. Changes in public policies that have encouraged inefficient use of land and water resources could help restore productivity.

Syria

Irrigation serves about 1 million ha in Syria out of an estimated total irrigation potential of 1.25 million ha (FAO, 2001a). Government irrigation projects cover an estimated 350 000 ha of irrigated land and a drainage system serves 78 percent of that land. Completed in 1975, the Euphrates Dam has the dual objective of generating electricity and providing water supply for 600 000 ha of irrigated farmland (Saliba, 1997). The high gypsum content of local soils, the high cost of reclaiming such soils and the withdrawal of lands from irrigation due to waterlogging and salinization have thwarted efforts to achieve the latter goal (Manners and Sagafi-Nejad, 1985; Hinnebusch, 1989b; Kolars, 1994; Soffer, 1999). Most farmers use surface irrigation methods on field crops and fruit trees, while sprinkler systems are in use on about 30 000 ha. Groundwater is the source of supply for an estimated 60 percent of the irrigated area, while surface water serves the remaining 40 percent. Many farmers drill their own wells in order to obtain a reliable irrigation supply. In 1994, there were an estimated 122 000 wells, of which 53 000 were unlicensed. Concerns regarding groundwater scarcity have generated greater interest in sprinkler and microirrigation systems in recent years. Most of the drainage development has occurred in the governorates bordering the Euphrates River, such as Al-Reqqa where 62 percent of the irrigated area has drainage. Salinization affected an estimated 60 000 ha of land in 1993, while waterlogging and salinity have led to the abandonment of about 5 000 ha in the Euphrates River basin. Work is underway to install open drainage systems in newly irrigated areas, with subsurface drains on 10 percent of these areas. The government is working to rehabilitate areas lost to waterlogging and salinity, given the relatively high cost of developing new areas for irrigation. Cropping patterns vary with average rainfall and the availability of irrigation water. The Al-Hassakeh governorate in the northeast produces more than half of Syria's wheat and cotton (Tutwiler, 1995). Farms in the region are large, many operations are mechanized, cereal monoculture is common, and wheat and barley together account for more than 80 percent of the arable area. Cereals account for about half of the arable area in the region around Aleppo and Hama, while food legumes, tree fruits, vegetables and industrial crops account for the other half. Many farmers in the region have installed tubewells to supplement irrigation of wheat, sugar beets and potatoes in the rainy season and to provide full irrigation of cotton and vegetables in the dry season.

Crop yields vary with the availability of irrigation water. In 1993, while the national average yield for irrigated wheat was 4 tonnes/ha, the average yields for rainfed wheat were 1.3 tonnes/ha for standard varieties and 2 tonnes/ha for HYVs (FAO, 2001a). The average yield of irrigated cotton was 3.1 tonnes/ha. More than half of the irrigated area in Syria was under wheat in 1993 (551 000 ha), while 200 000 ha of cotton and 130 000 ha of vegetables received irrigation that year. Most of Syria's cotton fields and 40 percent of its wheat fields receive irrigation, while barley is largely rainfed (EIU, 2001b). Hence, annual barley production varies substantially with changes in annual rainfall. The irrigated area in Syria generates more than 50 percent of the total value of agricultural production on less than 19 percent of the cultivated land.

In Syria, the level of fertilizer use increased by a factor of 25 since the early 1960s, while the irrigated area has doubled. Most of the increase in irrigated area has occurred since 1980, with a notable surge in area beginning in 1990. The rates of growth in fertilizer use has been stable since 1980, although fertilizer use may be reaching a plateau at a factor of about the three times the amount used in 1980.

Chapter 3

Factors affecting water and fertilizer use

Many factors affect the level and productivity of water and fertilizer use. Some relate more to water use, e.g. waterlogging, salinization, degradation, water table rise, drainage, seepage, and irrigation system design and maintenance. Some relate more to fertilizer use, e.g. nutrient imbalance, while others affect both water and fertilizer use, e.g. resource availability and management (inefficient use), crop rotations, soil fertility, research (and its dissemination), mechanization, weeds, disease, the use of HYVs, and the level of risk at farm level. Yet other factors affect water and fertilizer use at the macro level, e.g. the role of government through policy, subsidies, support prices, crop procurement programmes, tariffs and trade restrictions; the role of the private sector; and the related inequities and misallocations of market and non-market economies. These factors are relevant not only in the production context. Increasingly, they have come under scrutiny in relation to their importance to sustainability and ecological issues. This chapter reviews the factors in relation to their impacts on the water and fertilizer use in the three sample countries of Morocco, Pakistan and Syria.

OVERVIEW OF SAMPLE COUNTRIES

Irrigation is an essential input to crop production in Morocco, Syria and Pakistan as the average annual rainfall is not sufficient to support crop production in most areas. Irrigation has seen its most extensive development in Pakistan, where millions of farmers in the Indus River basin receive surface water supplies from the world's largest contiguous irrigation system. Many farmers in Punjab, Pakistan, use tubewells to augment their surface water supply with groundwater. In some areas, tubewells have enhanced agricultural productivity substantially, while in others the sustained use of poor-quality shallow groundwater has increased the pace at which soil salinity is reducing aggregate productivity in the Indus River basin.

The irrigated areas in Syria and Morocco are much smaller, but these areas produce a substantial proportion of agricultural output. Syria has been expanding its irrigation system in recent years, but the high gypsum content of soils in the Euphrates Valley has constrained improvements in productivity. Many farmers in Syria have installed wells and pumps to gain access to the nation's limited groundwater supplies. Overpumping of groundwater is threatening the sustainability of irrigated agriculture in some portions of the country.

The area irrigated in Morocco has not increased substantially in the last 20 years and rainfed lands generate most of the nation's agricultural output. Research and extension efforts to improve the productivity of land, fertilizer and water in rainfed areas in Syria and Morocco will enhance rural incomes and increase the likelihood that rural households will achieve and maintain food security.

All three sample countries have long implemented policies that modify farm-level input and output prices. Input subsidies, crop procurement programmes and trade restrictions can influence farm-level decisions regarding inputs and outputs substantially, with subsequent impacts on the observed productivity of land and water resources. These impacts can be particularly important in arid regions where scarce water supplies limit production opportunities and where the off-farm impacts of irrigation and drainage activities can degrade natural resources throughout a production region and over time.

Drainage is an essential input in regions where saline, shallow water tables contribute to soil salinization. Many irrigated areas lack adequate drainage systems. In the absence of prices or allocation policies that motivate efficient water use, regional problems of salinization and waterlogging develop before a drainage system is installed. The degradation of soil and water resources reduces the productivity of irrigation water, labour, fertilizer and other agricultural inputs. Some of the impacts of resource degradation appear soon after degradation begins, while other impacts develop over time.

Morocco

In Morocco, the extent of the nation's water resources will limit the future development of irrigation. Hence, much of the research regarding agriculture focuses on improving soil and water management in rainfed areas. In some years, small applications of irrigation water and chemical fertilizer may enhance yields substantially, while in other years very dry conditions at critical stages of crop development may negate any potential impact. The inherent riskiness of crop production in rainfed conditions acts as a constraint on farm-level fertilizer use. Research and policy programmes that reduce the farm-level financial risk of applying chemical fertilizer in rainfed areas may help improve agricultural productivity in Morocco.

Pakistan

In Pakistan, the introduction of HYVs of rice and wheat and the rapid adoption of intensive production methods generated substantial increases in crop yields during the 1960s and 1970s. However, gains in crop yields have been minimal in the last 20 years. The increase in areas affected by waterlogging and salinity and the decline in soil fertility in some areas have probably contributed to the declining rates of growth in crop yields. These problems are in part the result of: seepage of water from large, earthen canals; the extensive use of saline groundwater; and the inefficient use of water and fertilizer on farms. Successful efforts to reverse the declining growth rates will require policies and programmes that promote wiser use of limited resources, while maintaining the output required to sustain the livelihoods of rural residents and provide food supplies for urban areas.

The increases in crop production have not matched the rate of increase in irrigated area, largely because of inefficiencies and inequities in the water delivery system that have contributed to structural and environmental degradation (Mellor, 1996). Large seepage losses from canals and excessive irrigation with brackish shallow groundwater contribute to waterlogging and salinization, while the misallocation of water among regions and farmers reduces economic returns (Ahmad and Sampath, 1994; Qureshi *et al.,* 1994; Qureshi and Barrett-Lennard, 1998). Rising water tables and groundwater salinity may be important factors in agricultural productivity and sustainability in the Indus River basin (Shah *et al.,* 2001).

Poor quality groundwater, low fertilizer efficiency and increased losses to weeds and diseases have contributed to slower growth rates in crop yields in Pakistan (Byerlee and Siddiq, 1994). The degradation of soil and water resources that has occurred over a long period in Pakistan has probably contributed to the declining rates of growth in productivity. The problems of waterlogging and salinity are a concern in most arid regions. In the Indus River basin, the sustained use of saline groundwater for irrigation has probably accelerated the pace of soil salinization in some areas, contributing to the declining rates of growth in crop yields.

Other potential causes of the declining growth in productivity include the persistent planting of rice-wheat rotations. The ponding of water on rice fields degrades the quality of soil with respect to wheat production, leading to lower yields than those achieved where wheat rotates with other field crops. However, wheat yield reductions may also result where farmers delay the planting of wheat in order to maximize their cotton yields by obtaining an additional picking of their cotton fields in the late autumn season. Inappropriate nutrient applications may also have contributed to declining productivity growth rates. In particular, while the application of supplemental nitrogen has increased substantially since the 1960s, farmers have not always applied phosphorus, potassium and other nutrients in suitable proportions. As a result, the deficiency of one or more important nutrients may be reducing crop yields in some regions, even though farmers apply large amounts of supplemental nitrogen and other nutrients. A sustained effort to restore nutrient balance and to reduce the rate of increase in areas affected by waterlogging and salinity may help restore positive rates of growth in crop yields.

The government has subsidized the purchase of important inputs such as irrigation water, fertilizer, electricity, pesticides and seed for many years. However, it withdrew the subsidy on pesticides in the early 1980s and it has reduced fertilizer subsidies substantially in recent years. Subsidies remain in place for diesel and electric tubewells, purchased seeds, canal water and credit (Chaudhry and Sahibzada, 1995; Faruqee and Carey, 1995). The reduction and removal of input price subsidies in Pakistan in the 1980s caused substantial increases in farm-level input prices and reductions in farm-level net returns (Ahmad and Chaudhry, 1987; Looney, 1999).

The government's role in the supply of farm inputs also includes its activities in the importation, production and distribution of selected inputs. For example, the government imports and distributes phosphorus fertilizer and it produces a large portion of the seed required by farmers each year. Distortions caused by government intervention limit the supply of these inputs to farmers (Faruqee and Carey, 1995). Farm-level difficulties in acquiring the seeds of modern crop varieties and in obtaining sufficient phosphorus fertilizer for timely application have probably contributed to the declining rates of growth in crop yields. The government has traditionally supported the farm-level prices of all major crops through guaranteed minimum prices or other price support programmes (Khan, 1997). The government procures about 30 percent of the wheat produced each year at a predetermined support price and releases wheat flour to consumers through government-owned utility stores and through private markets (Kurosaki, 1996). There is also a price support scheme for basmati rice although much of this crop goes for export. In 2001, the government announced that it would remove price supports on all crops except wheat, rice, cotton and sugar cane. In addition, it plans to liberalize the market for wheat by 2003.

Private sector participation in the exporting of rice increased in the 1990s. The government discourages cotton production by imposing an export tax that prevents farmers from receiving the world price for their output. Removal of the export tax would stimulate cotton production, raise rural incomes and generate a more diverse set of rural, non-agricultural employment opportunities (Mellor, 1993). Cotton is a relatively profitable crop in Pakistan and requires less irrigation water than sugar cane does. Reducing the price support level for sugar, while at the same time reducing cotton export taxes, would generate greater net benefits and may reduce some of the pressure on land and water resources in the Indus River basin.

The intensification of agricultural production in Pakistan has stemmed largely from the development of small-scale and large-scale irrigation systems, the introduction of HYVs, mechanization and the use of chemical fertilizers and pesticides. Many farmers augment the surface water they divert from the Indus River canal system with groundwater pumped from private and public tubewells. The enhanced volume and reliability of irrigation water have enabled farmers to plant wheat and cotton or wheat and rice in continuous rotation for many years. The use of tractors and mineral fertilizer has increased in support of the higher intensity of cropping activities.

Irrigation with tubewells enhances productivity in regions with high-quality groundwater. However, productivity may decline over time in regions with brackish or saline groundwater where the supply of higher quality surface water is not sufficient to leach salts from the rootzone. The combination of higher cropping intensities and increased use of saline groundwater may substantially increase the rate at which salts accumulate in arid zone soils. Problems of water scarcity, waterlogging and salinity, inefficient water delivery and use, inequitable distribution and inadequate maintenance of the irrigation and drainage system limit the productivity of land and water in lower portions of the Indus River basin (Wescoat, 1991; Afzal, 1996; Ul-Haq and Shahid, 1997; Wambia, 2000; Kijne, 2001b). Salinization alone may reduce productivity by 25-70 percent on moderately affected soils and by almost 100 percent on severely affected soils (Ahmad *et al.*, 1998). Qureshi and Barrett-Lennard (1998) suggest that waterlogging and salinization affect 6.3 million ha in Pakistan, with direct impacts on the livelihoods of 16 million people.

The data examined by Ali and Byerlee (1999) suggest that soil and water quality in Punjab have declined since the 1960s. In particular, organic matter content and available phosphorus have decreased in soils, while the level of soluble salts has increased. At the same time, measures of residual carbonate and electrical conductivity of tubewell water have increased. Hence, although farmers have been applying more tubewell water in recent years than in the 1960s and 1970s, the salt content of irrigation water has increased substantially. The decline in resource quality has probably contributed to relatively low estimated rates of annual growth in TFP. These rates range from -0.50 percent per year for the wheat-rice rotation to 1.57 percent per year for the wheat-cotton rotation. The estimated aggregate rate of growth in TFP for the crop sector of Punjab is 1.26 percent per year. The authors suggest that growth in TFP would have been significantly higher in the absence of resource degradation.

The relatively low average productivity in Pakistan depends in part on the nation's limited water supply and the design of its irrigation system. In particular, the design concept underlying the Indus River basin irrigation system was one of providing 'protective' rather than 'full' irrigation potential (Jurriens and Mollinga, 1996). The aim was to prevent famine by maximizing the area served by the irrigation system, so that a large number of households would receive at least a partial irrigation supply (Johnson *et al.*, 1978; Johnson, 1982; Chohan, 1989; Mustafa, 2001). The original design was such that the system would be able to support subsistence agriculture at cropping intensities ranging from 50 to 75 percent (Ul-Haq and Shahid, 1997). However, cropping intensities have since risen beyond these levels as farmers have attempted to maximize economic returns to their limited land and water resources.

Profit-maximizing farmers who receive a partial irrigation supply that is not sufficient to generate maximum yield on all of their land will apply irrigation water to maximize the net return per unit of water received (Upton, 1994). This will occur when the incremental productivity of water is the same on all land parcels. Hence, farmers will attempt to spread a limited water supply across a larger land area than project planners imagined originally. Farmers will also augment surface water with groundwater where it is available at reasonable cost, thereby enabling them to diversify cropping patterns and increase cropping intensities.

Syria

The government plays a major role in many aspects of agricultural research, production and marketing in Syria (Springborg, 1981; Hinnebusch, 1989a). In particular, it has encouraged research into new technologies and it has implemented programmes to diffuse developments to farmers throughout the country. As a result, most technological adoption in Syrian agriculture since the 1960s has stemmed from top-down induced innovation rather than from individual farmers choosing new production methods to maximize their productivity (ISNAR, 1989). Primary inputs such as seeds, fertilizer, pesticides and credit are available to farmers through their participation in the government-operated Agricultural Cooperative Bank. One implication of this centralized structure of technological dissemination and input supply is that farm-level decisions will not reflect true profit-maximizing criteria such as the requirement that marginal productivity must equal the marginal cost of variable inputs. The government also plays a major role in planning crop rotations and determining the farm-level prices of inputs and outputs through its policies of input subsidies and output procurement (El-Akhrass, 1986). In general, the government boosts grain prices above world price levels to stimulate food crop production (Hinnebusch, 1997), while it extracts revenue from cotton farmers by paying them less than world prices for their produce. The government paid wheat farmers about 30 percent more than the world price in the early and middle 1980s, while maize farmers received more than twice the world price (World Bank, 1986). The government also maintains lower tariffs on agricultural inputs than on other imported goods in order to reduce production costs (Sukkar, 1998).

WATER USE IN MAJOR SCHEMES AND AT NATIONAL LEVEL

Morocco

Scheme development

Water is the primary constraint on the productivity and expansion of agriculture in Morocco. Rainfall is limited and variable and most of the cultivated area is without irrigation. However, Morocco has the most extensive river system in North Africa (Tuluy and Salinger, 1991) and its rivers have enabled the development of both traditional and modern irrigation systems. Traditional systems are in use in the high mountain valleys and foothills, while modern systems are in operation in the coastal plains and other lower lying areas (Funnell, 1994).

The government of Morocco has worked to increase irrigation potential, minimize the economic impacts of recurrent droughts, stimulate the production of export crops and improve rural incomes (Laamrani *et al.*, 2000). Acting in part on the recommendations of a 1964 World Bank mission, the government embarked upon a large-scale irrigation development programme in 1967 with the goal of irrigating 1 000 000 ha (Swearingen, 1987a). Public investments in irrigation increased substantially in the 1960s, contributing significantly to Morocco's rapid agricultural growth (Cleaver, 1982). For the 20 years following 1967, the irrigation expansion programme was the dominant feature of national development policy. The completion of most of the dams detailed in the expansion plan by 1986 brought more than 470 000 ha under perennial irrigation in large-scale irrigation schemes (Table 7). Within the major schemes, small-scale irrigation systems were irrigating an additional 155 000 ha, while small and medium-scale systems provided irrigation to 220 000 ha outside the major schemes, for a total irrigated area of almost 850 000 ha in 1986. In 1997, the area actually irrigated or under development in large irrigation schemes was 672 000 ha, while medium and small-scale schemes provided irrigation water to 332 000 ha (Table 8). In 1997, cereals accounted for 40 percent of the irrigated area while vegetables, olives and fodder crops accounted for more than 100 000 ha each (Table 9).

TABLE 7

Development of irrigated areas in large schemes in Morocco, 1956-1997

Irrigation perimeter	1956	1965	1975	1986	1997
			(ha)		
Gharb	10 500	28 000	54 200	87 300	106 350
Haouz-Tessaout	5 000	4 000	30 300	38 000	112 620
Tadla	20 000	62 300	97 500	109 400	109 000
Doukkala	300	11 000	28 200	63 000	69 600
Souss-Massa	-	7 000	11 700	25 700	39 900
Moulouya	-	11 500	45 500	69 000	77 280
Tafilalet	-	-	20 700	36 200	37 650
Loukkos	-	-	900	17 200	26 400
Ouarzazate	-	-	7 300	26 000	27 900
Total	35 800	123 800	296 300	471 800	606 700

Sources: Data for 1956-1986 from Swearingen, 1987a; data for 1997 from FAO, 2001c.

TABLE 8

Irrigated areas and irrigation methods in Morocco, 1997

Scheme size	Gravity systems	Sprinkler systems	Areas under development	Total area
		(ha)		
Large	470 425	121 775	79 500	671 700
Medium & small	325 110	690	6 500	332 300
Total area	795 535	122 465	86 000	1 004 000

Note: Areas under development are primarily gravity irrigation systems.

Source: FAO, 2001c.

TABLE 9

Irrigated areas and production of major crops in Morocco, 1997

	Production areas			Production		
Crop	Cultivated (ha)	Irrigated (ha)	Proportion irrigated (%)	Total output (1 000 tonnes)	Irrigated output (1 000 tonnes)	Proportion irrigated (%)
Cereals	6 074 000	404 000	7	952	111	12
Olives	402 000	126 000	31	62	25	41
Legumes	347 000	12 000	3	28	6	20
Vegetables	225 000	110 000	49	396	221	56
Fodder	171 000	126 000	73	855	667	78
Oil crops	98 000	36 000	37	9	5	53
Sugar	84 000	71 000	85	407	348	86
Citrus	73 000	73 000	100	132	132	100
Dates	23 000	23 000	100	6	6	100
Cotton	1 800	1 800	100	0.3	0.3	100
Other crops	484 000	20 000	4			
Total area	7 983 000	1 003 000	12.5			

Source: FAO, 2001c.

The 400 000 ha of irrigated cereal crops represent 7 percent of the total cereal production area cereals, while irrigation accounts for 49, 31 and 73 percent of the respective total area for vegetables, olives and fodder crops. The higher productivity of irrigated land in Morocco is evident in the proportions of total output generated in irrigated areas. For example, the 7 percent of cereal land that receives irrigation generates 12 percent of total cereal production. The corresponding proportions for irrigated vegetables, olives and fodder crops are 56, 41 and 78 percent.

Scheme management

Decentralized autonomous regional agencies are responsible for managing large-scale irrigation schemes in Morocco. Each agency is an Office Régional de Mise en Valeur Agricole (ORMVA). These agencies are responsible for the design, construction, operation and maintenance of irrigation networks, and they provide many of the productive services that farmers need (Smith, 1990). In addition, the ORMVAs supervise farming operations for industrial crops, distribute inputs and provide extension and mechanization services. The amounts and timing of fertilizer and other inputs made available to farmers probably vary among irrigation schemes according to the management performance of the individual ORMVAs and the degree to which they are able to recover the costs of operating and maintaining their facilities. The ORMVAs are generally responsible for operating and maintaining the main and secondary canals in large-scale irrigation systems, while farmers are responsible for maintaining the quaternary canals that bring water to individual fields. Inadequate operation and maintenance of the quaternary canals in some areas has led to reduced project and farm-level irrigation efficiencies. For example, in some areas of the Gharb irrigation scheme, farmers destroy the integrity of quaternary canals by cutting the banks to increase flow rates into their furrows (Lachhab and Essafi, 1989). Alterations in the shape and capacity of the canals degrade system performance. These activities and the inability of farmers to control furrow inflow rates accurately contribute to low farm-level irrigation efficiencies ranging from 44 to 65 percent.

Recent policy developments

Prior to implementing a structural adjustment programme in the mid-1980s, Morocco's intervention in agriculture policy favoured industry over agriculture, irrigated agriculture over rainfed agriculture, and consumers over agricultural producers (Tuluy and Salinger, 1991). The government determined the farm-level prices of many agricultural inputs and products and it required farmers in large-scale irrigation schemes to adhere to cropping patterns specified by the management of each irrigation command area (Cleaver, 1982). Pricing policies restricted the incomes of traditional farmers in rainfed areas. The government purchased their staple food crops at below-market prices, while farmers producing fruits and vegetables in irrigated areas were able to sell their products at market prices (Swearingen, 1987b). Farmers in irrigated areas may also have gained greater benefits from government subsidies on fertilizer, irrigation water, credit and selected types of farm machinery. The structural adjustment programme implemented in the 1980s brought reductions in input subsidies and higher prices for agricultural producers (de Janvry *et al.*, 1992). The government also increased its investments in rainfed agriculture, small and medium-scale irrigation projects and soil conservation projects (Rhazaoui, 1987). The incomes of both small and large farmers increased in the late 1980s, partly as a result of increases in producer prices and favourable rainfall conditions in 1985 and 1986 (Morrisson, 1991). The sum of irrigated areas within and outside government managed irrigation schemes increased from about 875 000 ha in 1961 to 1.3 million ha in 1999.

Pakistan

The Indus River basin irrigation system

Pakistan's canal irrigation system is the largest contiguous irrigation system in the world, with 60 000 km of canals and more than 80 000 watercourses, channels and ditches (Qureshi *et al.*, 1994). An estimated 130 000 million m^3 of water enter the canal system each year, but only 60 percent of it reaches farmgates because of inefficiencies in the delivery system (Faruqee, 1996). Extensive use of public and private tubewells that extract water from shallow aquifers helps augment the canal water supply. An estimated 29 000 million m^3 of groundwater with a salinity level of less than 1 500 mg/litre are available in the Indus River basin each year (Kijne and Kuper, 1995), but current extractions probably exceed that amount. In 1991, farmers used 46 000 million m^3 of groundwater for irrigation in the Indus River basin (Kijne, 2001a). Water is the input that limits the intensification of agriculture in Pakistan. Nearly 90 percent of Pakistan's irrigated area lies within the canal command area of the Indus River basin irrigation system. The irrigated area increased substantially during the 1970s and 1980s following completion of the Mangla, Chashma and Tarbela dams (Afzal, 1996) and with expansion of the area irrigated with private tubewells.

Overall

Between 1980 and 1999, the irrigated area in Pakistan increased from 14.7 to 18 million ha, while the total area planted with annual and permanent crops increased from 20.3 to 21.9 million ha. The irrigated area increased by about 25 percent in Punjab and NWFP, and by more than 50 percent in Balochistan. The irrigated area in Sindh has declined by more than 10 percent since 1980-81, possibly due to waterlogging and salinization problems in lower the reaches of the Indus River basin irrigation system.

The increase in the number of public and private tubewells from 186 000 in 1980-81 to more than 515 000 in 1998-1999 made a major contribution to enabling the 22-percent increase in total irrigated area in Pakistan. Since 1980, the number of tubewells has increased almost threefold in Punjab and Balochistan, by a factor of 2.4 in NWFP, while the cumulative rate of increase in Sindh has been 50 percent. At present, more than 90 percent (465 000) of Pakistan's private tubewells are in Punjab, while there about 20 000 tubewells in Sindh and Balochistan and 11 000 tubewells in NWFP.

Syria

Annual crops cover 4.27 million ha of the 4.94 million ha cultivated in Syria. Crop yields and total production can vary substantially with changes in annual rainfall, as most of the cultivated area is without irrigation. As a result, annual food production in Syria may be 5 percent less than average production in every third year (Richards and Waterbury, 1998). This inherent variability in rainfall and crop production has motivated substantial investments in irrigation and drainage projects since 1960.

The irrigated area in Syria has increased substantially since the 1960s as a result of large government investments in irrigation and drainage projects. In recent years, such investments have accounted for 60-75 percent of all government expenditure on agriculture (FAO, 1997). The irrigated area expanded from 45 000 ha in 1968 to 1.2 million ha in 1995. Since 1978, the irrigated area has increased from 2.9 to 6 percent of the country's total area, while the area irrigated with groundwater has increased from 226 000 to 560 000 ha. As in Pakistan, government subsidies have encouraged farmers to drill wells throughout the country, leading to problems of waterlogging and salinization in many areas.

Chapter 4
Resource use productivity

OVERVIEW OF EXPERIMENT AND SURVEY DATA

This chapter reviews specific studies on the impact of irrigation and fertilizer use on major crops (wheat, rice, maize, cotton, sugar beet and sugar cane) in the three sample countries. It also reviews studies on water conservation and on input and output elasticities for crops, irrigation and fertilizer, and discusses the contribution of other factors such as education. Some of the studies have examined the impact of irrigation, others have examined the impact of fertilizer use, and others the impact of irrigation combined with fertilizer use. Under these three headings, this section presents survey data and data from experiments by major crop rather than by country. Much of the empirical information presented here comes from national statistical agencies and international research centres. Data generated on experiment stations describe the potential yields that optimal management of water, fertilizer and other inputs can achieve, while data collected in farm-level surveys and case studies describe actual yields and input levels observed on farms in a given region or irrigation project.

Crop production conditions in a large portion of the Indus River basin, Pakistan, have degraded over a long period of time because of inappropriate management of soil and water resources, in part sustained by policies implemented to encourage rapid gains in productivity in the 1960s and 1970s (Pingali and Shah, 1999). The results of studies conducted at experiment stations may encourage public officials and farmers to make and sustain the considerable necessary investments to improve soil and water management practices and so help restore some of the lost productivity.

FERTILIZER

Farm-level nutrient ratios in many countries are often not optimal because of constraints involving knowledge, credit and access to fertilizer (Reuss and Johnson, 1978). In particular, nutrient deficiencies in Pakistan have become more extensive since the sharp reductions in fertilizer subsidies in the mid-1980s. Ahmad and Muhammad (1998) suggest that, with the exception of nitrogen in soils in Punjab, nutrient deficiencies pertaining to nitrogen, phosphate and potash increased in all four provinces between 1985-86 and 1995-96 (Table 10).

TABLE 10
Estimated nutrient deficiencies in Pakistan, 1985-86 and 1995-96

	Nitrogen		Phosphate		Potash	
	1985-86	1995-96	1985-86	1995-96	1985-86	1995-96
Province			(kg/ha)			
Punjab	19.19	8.57	10.45	10.73	23.69	27.27
Sindh	5.00	6.95	8.54	11.72	7.69	17.32
NWFP	9.52	10.73	8.35	10.74	20.89	29.73
Balochistan	21.56	27.15	7.43	11.36	14.18	25.57
Pakistan	15.61	9.39	9.78	10.90	20.00	25.79

Source: Ahmad and Muhammad, 1998.

Wheat

Arslan *et al*. (2000) examined the impact of nitrogen on crop yield for two high-yielding wheat cultivars at the Um Al-Mayathen experiment station, Syria, in 1994-95 and 1995-96. In general, higher nitrogen application rates generated higher grain yields, but marginal productivity diminished with some treatments. In the first season of the experiment, the yield increases with higher levels of nitrogen ranged from 5 to 7.6 percent, resulting in grain yields ranging from 7 018 to 8 065 kg/ha for the Sham3 cultivar (Table 11). There were no measurements for irrigation volumes, but a neutron probe did provide estimates of soil moisture. In terms of crop evapotranspiration, the estimated average productivity of water was 1.46 kg/m^3 for three of the four fertilizer treatments for the Sham3 cultivar. The average productivity of fertilizer declined with increases in the amount of nitrogen applied. Sham6 cultivar yields were lower with all treatments and, hence, the estimated average products of water and fertilizer were lower than those for the Sham3 cultivar.

TABLE 11
Wheat yields and water and fertilizer productivity, experiments at Um Al-Mayathen, Syria, 1994-95

Cultivar and treatment	Grain yield (kg/ha)	Evapotranspiration (m^3/ha)	Gross water use productivity (kg/m^3)	Gross fertilizer use productivity (kg/kg)
Triticum durum cv. Sham3				
Zero nitrogen	6 681	4 743	1.41	111.3
50% of recommended N	7 018	4 799	1.46	58.5
100% of recommended N	7 492	5 123	1.46	39.4
150% of recommended N	8 065	5 515	1.46	33.6
Triticum aestivum cv. Sham6				
Zero nitrogen	5 337	5 065	1.15	88.9
50% of recommended N	5 729	4 979	1.15	47.7
100% of recommended N	5 561	5 121	1.09	30.9
150% of recommended N	6 055	5 263	1.15	25.2

Notes: All treatments received 58.3 kg/ha P_2O_5, applied before planting and mixed with the surface soil. The recommended rate of nitrogen application was 120 kg/ha N and all nitrogen treatments used ammonium sulphate. Nitrogen fertilizer applications: one-third at complete emergence; and the remainder at complete tillering. A neutron probe measured moisture levels in all plots.

Sources: Arslan *et al*., 2000, as reported in FAO, 2001b.

TABLE 12
Wheat yields and water and fertilizer productivity, experiments at Um Al-Mayathen, Syria, 1995-96

Cultivar and treatment	Grain yield (kg/ha)	Evapotranspiration (m^3/ha)	Gross water use productivity (kg/m^3)	Gross fertilizer use productivity (kg/kg)
Triticum durum cv. Sham3				
Zero nitrogen	5 248	4 136	1.27	47.7
50% of recommended N	7 160	4 825	1.48	44.7
100% of recommended N	6 595	4 986	1.32	31.4
150% of recommended N	7 083	4 990	1.42	27.2
Triticum aestivum cv. Sham6				
Zero nitrogen	5 557	4 236	1.31	50.5
50% of recommended N	6 253	4 508	1.39	39.1
100% of recommended N	6 896	4 681	1.47	32.8
150% of recommended N	6 966	4 983	1.40	26.8

Notes: All treatments received 110 kg/ha P_2O_5, applied before planting and mixed with the surface soil. The recommended rate of nitrogen application was 100 kg/ha N and all nitrogen treatments used urea. Nitrogen fertilizer applications: one-third at complete emergence; and the remainder at complete tillering. A neutron probe measured moisture levels in all plots.

Sources: Arslan *et* al., 2000, as reported in FAO, 2001b.

The yields obtained with the Sham3 cultivar were smaller in the second year of the experiment, while the yields obtained with Sham6 were higher (Table 12). Both the yields and average input productivities were similar for the two cultivars in that year, particularly at the higher nitrogen applications. For example, the average yield obtained with either cultivar was about 7 000 kg/ha in the second year on plots receiving 150 kg/ha of nitrogen. In comparison with the zero nitrogen treatment, the incremental yield obtained by applying 50 percent of the recommended nitrogen increased for both cultivars in the second year. In particular, the incremental gains were 5 and 7 percent in the first year and 36 and 13 percent in the second year.

Maize

Khalifa and Mohammed (1991) conducted an analysis of maize yields in the lower Euphrates River basin, Syria, between 1985 and 1986. In both years, maize yields were substantially higher on all plots receiving 80 or 160 kg/ha of nitrogen compared with plots receiving no supplemental nitrogen (Tables 13 and 14).

Yields exceeded 5 000 kg/ha on all treatments except one receiving 160 kg/ha of nitrogen even without supplemental phosphorus. Yields exceeded 6 000 kg/ha on plots receiving 160 kg/ha of nitrogen and 40 kg/ha of phosphate. In general, the average productivity of nitrogen was higher at applications of 80 kg/ha than at applications of 160 kg/ha. The average productivities of phosphorus and potassium increased monotonically with increases in nitrogen application, for a given application of phosphorus. The highest average productivity of phosphorus fertilizer occurred at an application rate of 40 kg/ha of phosphorous while the average productivity of potassium did not vary systematically with changes in phosphorus applications.

TABLE 13
Average products of fertilizers in maize production, lower Euphrates River basin, Syria, 1985

Treatment	Yield (kg/ha)	Estimated average products of individual nutrients Nitrogen (kg/kg)	Phosphorus (kg/kg)	Potassium (kg/kg)
No supplemental P_2O_5				
0 kg/ha N	2 027	n.d.	n.d.	12.7
80 kg/ha N	3 822	47.8	n.d.	23.9
160 kg/ha N	5 400	33.8	n.d.	33.8
40 kg/ha of P_2O_5				
0 kg/ha N	2 245	n.d.	56.1	14.0
80 kg/ha N	5 632	70.4	140.8	35.2
160 kg/ha N	6 780	42.4	169.5	42.4
80 kg/ha of P_2O_5				
0 kg/ha N	2 315	n.d.	28.9	14.5
80 kg/ha N	4 617	57.7	57.7	28.9
160 kg/ha N	5 757	36.0	72.0	36.0
160 kg/ha of P_2O_5				
0 kg/ha N	2 100	n.d.	13.1	13.1
80 kg/ha N	3 832	47.9	24.0	24.0
160 kg/ha N	5 030	31.4	31.4	31.4

Notes: Phosphorus applied as triple superphosphate before planting. All treatments received 160 kg/ha K_2O as potassium sulphate, also applied before planting. Nitrogen fertilizer applications: one-third of each treatment by hand 25 days after planting; and the remainder two months after planting. Farmers' traditional irrigation methods were used and the maize ears were hand-harvested. Soil at the site was affected slightly by salts: electrical conductivity (EC_e) of 2.51 in the upper 15 cm.

Source: Khalifa and Mohammed, 1991, as reported in FAO, 2001b.

TABLE 14

Average products of fertilizers in maize production, lower Euphrates River basin, Syria, 1986

Treatment	**Yield** (kg/ha)	**Estimated average products of individual nutrients** **Nitrogen** (kg/kg)	**Phosphorus** (kg/kg)	**Potassium** (kg/kg)
No supplemental P_2O_5				
0 kg/ha N	2 237	n.d.	n.d.	14.0
80 kg/ha N	4 237	53.0	n.d.	26.5
160 kg/ha N	5 642	35.3	n.d.	35.3
40 kg/ha of P_2O_5				
0 kg/ha N	2 317	n.d.	57.9	14.5
80 kg/ha N	5 657	70.7	141.4	35.4
160 kg/ha N	6 185	38.7	154.6	38.7
80 kg/ha of P_2O_5				
0 kg/ha N	2 195	n.d.	27.4	13.7
80 kg/ha N	4 582	57.3	57.3	28.6
160 kg/ha N	5 660	35.4	70.8	35.4
160 kg/ha of P_2O_5				
0 kg/ha N	1 932	n.d.	12.1	12.1
80 kg/ha N	4 010	47.9	25.1	25.1
160 kg/ha N	4 655	29.1	29.1	29.1

Notes: Phosphorus applied as triple superphosphate before planting. All treatments received 160 kg/ha K_2O as potassium sulphate, also applied before planting. Nitrogen fertilizer applications: one-third of each treatment by hand, 25 days after planting; and the remainder two months after planting. Farmers' traditional irrigation methods were used and the maize ears were hand-harvested. Soil at the site was slightly affected by salts: electrical conductivity (EC_e) of 1.20 in the upper 15 cm.

Source: Khalifa and Mohammed, 1991, as reported in FAO, 2001b.

Sugar beet

Sharanek (1990) examined the impact of alternative nitrogen treatments on the root and sugar yields of sugar beets at the Abou Jarach Farm at the University of Damascus, Syria. The average root yields obtained with autumn-planted sugar beets increased from 44 000 to 49 900 kg/ha and the average sugar yields increased from 6 300 to 7 300 kg/ha as the nitrogen application increased from zero to 180 kg/ha (Table 15). The proportional increases in yield were smaller than the proportional increases in nitrogen applications, causing the average productivity of fertilizer to decline throughout the range of treatments. Increasing the nitrogen application from 180 to 240 kg/ha generated a 9-percent increase in root yield, but the sugar yield declined by 2.7 percent. Hence, it would not have been economically rational to apply more than 180 kg/ha of nitrogen. That treatment generated only a 2.8 percent increase in sugar yield above the yield obtained when applying 120 kg/ha of nitrogen. The economically optimal nitrogen application, which is a function of the relative prices of sugar beets and nitrogen, was probably between 120 and 180 kg/ha. Sharanek (1990) also examined the impact of nitrogen application on spring-planted sugar-beet yields in a second study at the Abou Jarach Farm. Banding 120 kg/ha of nitrogen rather than broadcasting the fertilizer increased the average sugar yield from 8 100 to 9 800 kg/ha. Both yields exceeded the sugar yield obtained on plots receiving no supplemental nitrogen. The average productivity of fertilizer was higher for the banded treatments, as the amount of fertilizer applied was the same for both treatments.

IRRIGATION

Wheat

Bushmakh *et al.* (1997) compared wheat yields and water use on rainfed plots with plots irrigated at 50, 75 and 100 percent of full irrigation at the Surbaya experiment station in Aleppo, Syria.

TABLE 15

Sugar-beet yields in small basins, Abou Jarach Farm, University of Damascus, Syria, 1985-87

Irrigation treatment	**Root yield**	**Sugar yield**	**Average products of fertilizer**	
			Roots	**Sugar**
	(kg/ha)	(kg/ha)	(kg/kg)	(kg/kg)
Autumn-planted sugar beets				
No supplemental N	44 000	6 300	177.6	25.20
60 kg/ha N	46 900	6 400	151.3	20.65
120 kg/ha N	49 700	7 100	134.3	19.19
180 kg/ha N	49 900	7 300	116.0	16.98
240 kg/ha N	54 200	7 100	110.6	14.49
Spring-planted sugar beets				
No supplemental N	55 400	7 600	230.8	31.67
120 kg/ha N				
Broadcast	62 200	8 100	172.8	22.50
Banded	70 800	9 800	196.7	27.22

Notes: Autumn-planted treatments received 130 kg/ha of P_2O_5 as triple superphosphate (46%) and 120 kg/ha of K_2O as potassium sulphate (21%). Spring-planted treatments received 120 kg/ha of P_2O_5 as triple superphosphate (46%) and 120 kg/ha of K_2O as potassium sulphate (21%). Fertilizer broadcast and mixed with the surface soil before planting. Two nitrogen applications: one after emergence; and one after thinning. Autumn planting dates: between 20 October and 11 November each year. Spring planting dates: between 20 February and 3 March. No accurate measurement of irrigation water on either set of treatments.

Source: Sharanek, 1990, as reported in FAO, 2001b.

The average crop evapotranspiration on rainfed plots was 455 mm, or an equivalent water application of 4 550 m^3/ha (Table 16). The 50-percent irrigation treatment generated an average grain yield of 3 830 kg/ha, or 35 percent more grain than on the rainfed plots. The 75-percent irrigation treatment generated an additional 46 percent gain in yield, while full irrigation generated an incremental 15-percent gain in yield. The estimated average products of applied water and fertilizer increase with the volume of irrigation water applied, as proportional gains in yield are greater than proportional increases in applied water and the amount of fertilizer is the same for all irrigation treatments. The estimated irrigation efficiencies are at least 80 percent for all three irrigation treatments. These results suggest that careful irrigation water management can improve wheat yields substantially above those on rainfed fields.

Zhang and Oweis (1999) examined the role of supplemental irrigation and optimal irrigation scheduling on wheat yields in a series of experiments at the ICARDA research station in Tel Hadya, Syria, between 1985 and 1996. Annual rainfall during the period ranged from 230 mm in 1988/89 to 504 mm in 1987/88. Seasonal evapotranspiration ranged from 200 to 460 mm for rainfed durum and bread wheat, with grain yields ranging from 0.35 to 4.0 tonnes/ha for bread wheat and from 0.6 to 5.0 tonnes/ha for durum wheat. With supplemental irrigation, seasonal evapotranspiration ranged from 300 to 650 mm and grain yields ranged from 2.3 to 7.5 tonnes/

TABLE 16

Water and fertilizer productivity in wheat production, Surbaya Station, Aleppo, Syria, 1992-96

Irrigation treatment	**Grain yield** (kg/ha)	**Water applied** (m^3/ha)	**Applied wateruse productivity** (kg/m^3)	**Gross fertilizer use productivity** (kg/kg)
Full irrigation	6 450	8 524	0.76	30.7
75% irrigation	5 610	7 729	0.73	26.7
50% irrigation	3 830	6 854	0.56	18.2
Rainfed	2 840	4 550	0.62	23.5

Note: All treatments received 100 kg/ha of P_2O_5 and 110 kg/ha of N.

Sources: Bushmakh *et al.*, 1997, as reported in FAO, 2001b.

ha for bread wheat and from 3.6 to 8.4 tonnes/ha for durum wheat. The authors estimated linear regression equations in which the incremental gains in grain yield due to a 10-mm increase in evapotranspiration were 160 kg/ha for bread wheat and 116 kg/ha for durum wheat. Estimates of quadratic yield functions, in which the independent variable is the sum of seasonal rainfall and supplemental irrigation, made use of grain yield data for the Cham 4 (bread wheat) and Cham 1 (durum wheat) cultivars. These functions combine with estimated cost functions to describe the timing and amounts of supplemental irrigation that will maximize grain yield or profit at various levels of seasonal rainfall. For example, if seasonal rainfall were 350 mm, supplemental irrigation of 330 mm would achieve the maximum yield of bread wheat, while 236 mm would obtain the maximum profit in a land-constrained situation, and 160 mm would achieve the maximum yield with a limited water supply. The analogous values for durum wheat are 410, 354 and 244 mm of supplemental irrigation. The analysis presented by Zhang and Oweis (1999) demonstrates the importance of selecting an appropriate goal with respect to supplemental irrigation and grain yields, particularly in a region with limited water supplies.

Sugar beet

Bouaziz (2001) reported average sugar-beet root yields ranging from 61 to 91 tonnes/ha on experimental plots in Morocco irrigated with different amounts of irrigation water applied during the season (Table 17). The lowest yield was with one irrigation of 600 m^3/ha of supplemental irrigation water, while the highest yield was with three irrigations providing a

TABLE 17

Sugar-beet yields and the productivity of water on plots in Morocco

Irrigation treatment	Water applied	Water consumed	Crop yield		Average product of applied water	
			Roots	Sugar	Roots	Sugar
	(m^3/ha)	(m^3/ha)	(kg/ha)	(kg/ha)	(kg/m^3)	(kg/m^3)
T 100% (4)	2 400	5 759	85 420	13 670	14.8	2.37
T 80% (3)	1 800	5 449	91 170	14 200	16.7	2.61
T 60% (3)	1 800	5 223	79 180	11 990	15.2	2.30
T 40% (1)	600	4 968	61 300	9 250	12.3	1.86
Farmer's practice (3)	1 800	5 279	74 270	10 940	14.1	2.07

Note: In parentheses, the number of irrigation events.

Source: FAO, 2001c.

TABLE 18

Sugar-beet yields and the productivity of water on plots in Morocco

Irrigation treatment	No. of irrigations	Water consumed	Crop yield		Average product of applied water	
			Roots	Sugar	Roots	Sugar
	(m^3/ha)	(m^3/ha)	(kg/ha)	(kg/ha)	(kg/m^3)	(kg/m^3)
SB G1 - BAS	2	4 400	32 800	5 910	7.38	1.33
SB G2 - BAS	2	5 550	54 180	9 200	9.76	1.65
SB G3 - BAS	5	5 780	69 520	10 660	12.02	1.84
ZM A1 - BAS	6	5 670	47 600	7 850	8.39	1.38
ZM A2 - BAS	5	5 360	41 600	7 660	7.76	1.42
FH G1 - BAS	3	5 551	40 000	8 310	7.20	1.49
FH G2 - BAS	4	4 790	42 500	7 480	8.87	1.56
FH A1 - BAS	7	5 426	53 600	9 140	9.88	1.68
FH A2 - BAS	7	5 720	48 700	9 050	8.51	1.58

Source: FAO, 2001c.

total of 1 800 m^3/ha. A fourth irrigation providing an additional 600 m^3/ha did not improve crop yield beyond the level achieved with three irrigations. The highest average products of water, with respect to both roots and sugar, were also with three irrigations. In a second study reported by Bouaziz (2001), five irrigation events resulted in the highest average yield and the highest average productivity of water (Table 18). The highest average yield was 69.5 tonnes/ha of roots, or 10.7 tonnes/ha of sugar. The average products of water for this treatment were 12.02 kg/m^3 (roots) and 1.84 kg/m^3 (sugar).

IRRIGATION AND FERTILIZER

Wheat

Oweis *et al.* (1998) examined the roles of nitrogen and supplemental irrigation on both rainfed and irrigated wheat production in northern Syria between 1992 and 1996. Yield response to nitrogen varied with moisture conditions and sowing date. The yield increases were significant with supplemental nitrogen up to 50 kg/ha on rainfed plots and up to 100 kg/ha on irrigated plots. Adding one-third of full irrigation increased wheat yields significantly above the yield obtained on rainfed plots, while adding two-thirds of full irrigation was sufficient to generate yield approaching the maximum. The authors concluded that it would be possible to increase and stabilize wheat yields in the region with minimal irrigation and fertilizer inputs. In their study, the yield on rainfed plots rose by almost 100 percent as a result of applying one-third of a full irrigation and 100 kg/ha of nitrogen.

Oweis *et al.* (2000) examined the roles of nitrogen, supplemental irrigation and sowing date on wheat yields and water use efficiency at the ICARDA research station at Tel Hadya, Syria, between 1992 and 1996. Sowing dates were about one month apart in November, December and January during each of four production seasons. In general, wheat yields increased with increases in applied water and nitrogen, although the incremental gains achieved with each input diminished or became negative at higher application levels. Water use efficiency ranged from 0.25 to 2.34 kg/m^3 varying with the amounts of nitrogen and supplemental irrigation applied and with the sowing date. In particular, the water use efficiency of supplemental irrigation increased with increasing nitrogen up to 150 kg/ha on wheat planted in November or December. Water use efficiency increased with nitrogen up to 100 kg/ha on wheat planted in January. Water use efficiency increased when applied water increased from one-third to two-thirds of full irrigation, but it declined sharply at full irrigation with the November sowing. Water use efficiency declined after one-third of full irrigation with wheat planted in December or January. The authors concluded that efforts to satisfy full irrigation in northern Syria and other Mediterranean environments are probably not efficient. Applying one-third or two-thirds of full irrigation requires substantially less water than full irrigation and the additional yield achieved with full irrigation may not justify the additional water applied. Subsequent testing of the findings on 14 farm fields in Syria between 1996 and 1999 found that wheat yields declined by 10-15 percent with supplemental irrigation limited to 50 percent of full irrigation. In some settings, it is possible to enhance the water use efficiency of supplemental irrigation by staggering the planting of wheat fields, so that peak water demands occur during a longer period in spring (Oweis and Hachum, 2001). The reduction in the size and cost of the irrigation system needed to supply peak water demands may be sufficient to justify the reduction in yield caused by the delayed planting.

As less than 10 percent of the area planted with cereals and legumes in Morocco receives irrigation, efforts to improve the productivity of precipitation and fertilizer in rainfed areas may generate substantial gains in aggregate output and enhance food security. Applying fertilizer and other inputs in non-irrigated areas where rainfall is minimal and variable involves a degree of risk that many farmers are not willing or able to accommodate. In a visual survey of 2 152 fields in Morocco in 1990, Ryan *et al.* (1992) found that the proportion of wheat fields receiving adequate nitrogen declined from 19 percent in an area with an annual rainfall of 500 mm to 9 percent in an area with an annual rainfall of 270 mm. The proportions of wheat fields considered severely deficient in nitrogen were 20 and 41 percent in the two areas. They observed similar differences in nitrogen availability on barley fields. The proportion of adequately fertilized fields declined from 27 to 5 percent, while the proportion of severely deficient fields increased from 29 to 46 percent, as annual rainfall declined from 390 to 240 mm. Applying supplemental nitrogen may increase wheat yields in rainfed areas significantly, although results each year will vary with rainfall and the extent of Hessian fly infestation (Ryan *et al.*, 1997). Ryan *et al.* (1998) suggest that 40 kg/ha of nitrogen is sufficient to achieve maximum wheat yields in some years, while Ryan *et al.* (1997) found significant yield response up to 90 kg/ha of nitrogen. Abdel Monem *et al.* (1990) obtained significant yield improvements with a nitrogen application of 100 kg/ha.

Barley and triticale grown in rainfed areas also respond positively to supplemental nitrogen. Ryan *et al.* (1991) suggest that nitrogen applications up to 90 kg/ha may generate economically attractive yield improvements in favourable rainfall areas (annual rainfall greater than 350 mm). Nitrogen applications up to 30 kg/ha may be profitable in marginal rainfall areas (annual rainfall between 250 and 350 mm), while nitrogen may not improve barley yields in areas with an annual rainfall of less than 250 mm. Ryan *et al.* (1991) suggest that the likelihood of achieving positive economic returns with supplemental nitrogen is greater in the case of barley or triticale than for wheat, because barley and triticale have greater drought resistance and are tolerant of Hessian fly damage.

Al-Shawa and Malakani (2001) examined the role of irrigation and fertilizer in wheat production from 1995/96 to 1997/98 in the Al-Yarmook basin in southern Syria. They examined five levels of supplemental nitrogen and four irrigation treatments. In general, wheat yields increased with additional irrigation events within each fertilizer treatment (Table 19). On all treatments involving some supplemental nitrogen, the incremental returns to irrigation diminished with each irrigation event. The estimated gross water use productivity generally increases with the number of irrigation events within a fertilizer treatment because that measure is defined as grain yield divided by evapotranspiration, which increases with the number of irrigation events. It is possible to determine the economically optimal number of irrigations by comparing the value of incremental yield obtained with an additional irrigation event with the incremental cost of irrigation. Farmers will consider the farm-level cost of obtaining and applying irrigation water, while a public agency should also consider the opportunity cost of water made available for use in agriculture. Table 19 presents the data according to irrigation treatment while Table 20 presents a different arrangement to show how incremental yields change with increases in supplemental nitrogen within a given irrigation treatment. On rainfed plots, each increment of 20 kg/ha of nitrogen adds at least 260 kg/ha of grain yield. The largest yield increment of 370 kg/ha occurred when the nitrogen application increased from 40 to 60 kg/ha. Diminishing incremental returns to nitrogen are more evident on the irrigated treatments. For example, the first two increments of nitrogen added 150 and 760 kg/ha on plots irrigated once, while the second two increments of nitrogen added 20 and 100 kg/ha of grain yield. As a result, the gross water use productivity remained relatively constant above 40 kg/ha of nitrogen, while the gross fertilizer use productivity declined as the nitrogen application increased beyond 40 kg/ha. The incremental productivities of the last two 20 kg/ha increments of nitrogen were -70 and 120 kg/

TABLE 19

Fertilizer and water productivity in wheat production, Al-Yarmook basin, Syria, 1995-96 to 1997-98, by irrigation treatment

	Grain yield (kg/ha)	**Evapotranspiration** (ET_a, m^3/ha)	**Gross water use productivity** (kg/m^3)	**Gross fertilizer use productivity** (Ratio)
Zero kg/ha N				
Rainfed	1 850	2 525	0.73	(n/a)
One irrigation	2 800	2 992	0.94	(n/a)
Two irrigations	3 020	3 258	0.93	(n/a)
Three irrigations	3 490	3 525	0.99	(n/a)
20 kg/ha N				
Rainfed	2 110	2 525	0.84	6.93
One irrigation	2 950	2 992	0.99	9.69
Two irrigations	3 690	3 258	1.13	12.12
Three irrigations	4 010	3 525	1.14	13.17
40 kg/ha N				
Rainfed	2 400	2 525	0.95	3.94
One irrigation	3 710	2 992	1.24	6.10
Two irrigations	4 490	3 258	1.38	7.38
Three irrigations	4 470	3 525	1.27	7.34
60 kg/ha N				
Rainfed	2 770	2 525	1.10	3.03
One irrigation	3 730	2 992	1.25	4.09
Two irrigations	4 420	3 258	1.36	4.84
Three irrigations	4 880	3 525	1.38	5.34
80 kg/ha N				
Rainfed	3 050	2 525	1.21	2.51
One irrigation	3 830	2 992	1.28	3.15
Two irrigations	4 540	3 258	1.39	3.73
Three irrigations	4 680	3 525	1.33	3.84

Source: Al-Shawa and Malakani, 2001, as reported in FAO, 2001b.

ha on plots irrigated twice and 410 and -200 kg/ha on plots irrigated three times. Hence, it would not be efficient to apply more than 60 kg/ha of nitrogen on the plot irrigated three times. It may also be inefficient to apply more than 40 kg/ha of nitrogen on the plot irrigated twice. In 2001, the incremental cost of a 20 kg/ha N application was US$2.41 at the average currency exchange rate (EIU, 2001b). If the world price of wheat is US$3.00 per bushel (0.027 tonnes), then the incremental yield needs to be 22 kg/ha to justify the incremental cost of urea. The cost of labour and machinery required to apply the urea are also pertinent factors in deciding whether to apply an additional 20 kg/ha of nitrogen. The results provided by Al-Shawa and Malakani (2001) suggest that both irrigation and nitrogen can generate substantial increases in the grain yield of wheat, but both inputs are subject to diminishing marginal returns.

Garabet *et al*. (1995) obtained similar results regarding the incremental productivity of nitrogen fertilizer and irrigation water from a two-year study of wheat production at Tel Hadya in northern Syria. Irrigation treatments included rainfed plots receiving no supplemental irrigation and plots irrigated using 33, 66 or 100 percent of the water required to achieve field capacity at each irrigation event. Fertilizer treatments included 0, 50, 100 and 150 kg/ha of supplemental nitrogen. Annual rainfall in the first year of the study was 325 mm and the yield on non-irrigated plots receiving no supplemental nitrogen was 2 800 kg/ha compared with 3 500 kg/ha on rainfed plots receiving 50 kg/ha of nitrogen (Table 21). However, additional nitrogen

TABLE 20

Fertilizer and water productivity in wheat production, Al-Yarmook basin, Syria, 1995-96 to 1997-98, by nitrogen application

Treatment	**Grain yield** (kg/ha)	**Evapotranspiration** (ET_a, m^3/ha)	**Gross water use productivity** (kg/m^3)	**Gross fertilizer use productivity** (Ratio)
Rainfed				
Zero kg/ha N	1 850	2 525	0.73	(n/a)
20 kg/ha N	2 110	2 525	0.84	6.93
40 kg/ha N	2 400	2 525	0.95	3.94
60 kg/ha N	2 770	2 525	1.10	3.03
80 kg/ha N	3 050	2 525	1.21	2.51
One irrigation				
Zero kg/ha N	2 800	2 992	0.94	(n/a)
20 kg/ha N	2 950	2 992	0.99	6.69
40 kg/ha N	3 710	2 992	1.24	6.10
60 kg/ha N	3 730	2 992	1.25	4.09
80 kg/ha N	3 830	2 992	1.28	3.15
Two irrigations				
Zero kg/ha N	3 020	3 258	0.93	(n/a)
20 kg/ha N	3 690	3 258	1.13	12.12
40 kg/ha N	4 490	3 258	1.38	7.38
60 kg/ha N	4 420	3 258	1.36	4.84
80 kg/ha N	4 540	3 258	1.39	3.73
Three irrigations				
Zero kg/ha N	3 490	3 525	0.99	(n/a)
20 kg/ha N	4 010	3 525	1.14	13.17
40 kg/ha N	4 470	3 525	1.27	7.34
60 kg/ha N	4 880	3 525	1.38	5.34
80 kg/ha N	4 680	3 525	1.33	3.84

Source: Al-Shawa and Malakani, 2001, as reported in FAO, 2001b.

applications in excess of 50 kg/ha did not generate higher yields on the rainfed plots in the first year of the study. In general, grain yields increased with the volume of irrigation water applied within a given fertilizer treatment, although diminishing marginal returns are evident in several of the treatments. For example, on plots receiving no supplemental nitrogen, there was no significant difference in grain yield on plots irrigated with 33, 66 or 100 percent of the water required to restore field capacity. On plots receiving 100 or 150 kg/ha of nitrogen, irrigations to restore field capacity did not produce a significant yield increase beyond that achieved by irrigating with 66 percent of the water required to restore field capacity. The full irrigation treatment did increase grain yield by 600 kg/ha on plots receiving 50 kg/ha of nitrogen, resulting in an average yield of 5 300 kg/ha. That yield is similar to the average yields achieved with 100 or 150 kg/ha of nitrogen and irrigating with 66 or 100 percent of the water required to restore field capacity. Table 21 presents the data according to irrigation treatment while Table 22 shows how incremental yields change with increases in supplemental nitrogen within a given irrigation treatment. In general, there is little variation in the average productivity of water use within or across fertilizer treatments on plots receiving some supplemental nitrogen. The average productivity of fertilizer declines with increases in nitrogen application because the proportional increase in crop yield is substantially smaller than the proportional increase in fertilizer applied.

The rainfall received in the second year of the study at Tel Hadya was 275 mm and the grain yield achieved on rainfed plots receiving no supplemental nitrogen declined to 1 600 kg/ha (Table 23). As a result, the incremental productivity of the first irrigation treatment was higher

TABLE 21

Fertilizer and water productivity in wheat production, Tel Hadya, Syria, year one, by irrigation treatment

Rainfall = 325 mm **Treatment**	**Grain yield** (kg/ha)	**Irrigation plus rainfall** (m^3/ha)	**Gross water use productivity** (kg/m^3)	**Gross fertilizer use productivity** (kg/kg)
Zero kg/ha N				
Rainfed	2 800	3 230	0.87	70.0
A: irrigated using 33% of the water applied to C	3 500	3 779	0.93	87.5
B: irrigated using 66% of the water applied to C	3 500	4 327	0.81	87.5
C: irrigated to field capacity during each irrigation event	3 600	4 876	0.74	90.0
50 kg/ha N				
Rainfed	3 500	3 230	1.08	38.9
A: irrigated using 33% of the water applied to C	4 000	3 779	1.06	44.4
B: irrigated using 66% of the water applied to C	4 700	4 327	1.09	52.2
C: irrigated to field capacity during each irrigation event	5 300	4 876	1.09	58.9
100 kg/ha N				
Rainfed	3 300	3 230	1.02	23.6
A: irrigated using 33% of the water applied to C	4 500	3 779	1.19	32.1
B: irrigated using 66% of the water applied to C	5 200	4 327	1.00	37.1
C: irrigated to field capacity during each irrigation event	5 200	4 876	1.07	37.1
150 kg/ha N				
Rainfed	3 400	3 230	1.05	17.9
A: irrigated using 33% of the water applied to C	4 400	3 779	1.16	23.2
B: irrigated using 66% of the water applied to C	5 500	4 327	1.27	29.0
C: irrigated to field capacity during each irrigation event	5 600	4 876	1.15	29.5

Note: All treatments, including N = 0 plots, received 40 kg/ha P_2O_5 as triple superphosphate.

Source: Garabet *et al.*, 1995, as reported in FAO, 2001b.

in that year, ranging from 800 kg/ha on plots receiving no supplemental nitrogen to 2 300 kg/ha on plots receiving 150 kg/ha of nitrogen. Incremental returns were positive for all irrigation treatments at all levels of nitrogen applications. As a result, the average productivity of fertilizer increased with larger amounts of irrigation water within each fertilizer treatment.

Table 24 presents data from the second year where the diminishing marginal returns to fertilizer use within a given irrigation treatment are evident. In particular, supplemental nitrogen did not generate a significant yield increase on rainfed plots in the second year, when the rainfall totalled 275 mm. The first 50 kg/ha of nitrogen increased the grain yield by 800 kg/ha on plots irrigated using 33 percent of the water required to restore field capacity. However, higher levels of fertilizer application beyond 50 kg/ha did not generate further increases in yield. The incremental returns to fertilizer were positive through to 100 kg/ha and 150 kg/ha on plots irrigated using 66 or 100 percent of the water required to restore field capacity, although the incremental yield gain on the latter set of plots was 100 kg/ha. In general, there was little variation in the average productivity of water within irrigation treatments at positive levels of nitrogen application. Most values are within the range of 0.85 to 1.07 kg/m^3. The average productivity of fertilizer declines with the amount of nitrogen applied within each irrigation treatment because, even when yield gains are positive, the proportional increase in yield is smaller than the proportional increase in nitrogen applied. The results provided by Garabet *et al.* (1995) confirm the potential improvements in wheat yields from using fertilizer and irrigation in northern Syria. The incremental returns to irrigation will be greater in drier years, while the incremental returns to both irrigation and nitrogen fertilizer will decline at higher levels of each input in both dry and wet years.

TABLE 22

Fertilizer and water productivity in wheat production, Tel Hadya, Syria, year one, by nitrogen application

Rainfall = 325 mm **Treatment**	**Grain yield** (kg/ha)	**Irrigation plus rainfall** (m^3/ha)	**Gross water use productivity** (kg/m^3)	**Gross fertilizer use productivity** (kg/kg)
Rainfed				
Zero kg/ha N	2 800	3 230	0.87	70.0
50 kg/ha N	3 500	3 230	1.08	38.9
100 kg/ha N	3 300	3 230	1.02	23.6
150 kg/ha N	3 400	3 230	1.05	17.9
A: irrigated using 33% of the water applied to C				
Zero kg/ha N	3 500	3 779	0.93	87.5
50 kg/ha N	4 000	3 779	1.06	44.4
100 kg/ha N	4 500	3 779	1.19	32.1
150 kg/ha N	4 400	3 779	1.16	23.2
B: irrigated using 66% of the water applied to C				
Zero kg/ha N	3 500	4 327	0.81	87.5
50 kg/ha N	4 700	4 327	1.09	52.2
100 kg/ha N	5 200	4 327	1.00	37.1
150 kg/ha N	5 500	4 327	1.27	29.0
C: irrigated to field capacity during each irrigation event				
Zero kg/ha N	3 600	4 876	0.74	90.0
50 kg/ha N	5 300	4 876	1.09	58.9
100 kg/ha N	5 200	4 876	1.07	37.1
150 kg/ha N	5 600	4 876	1.15	29.5

Note: All treatments, including N = 0 plots, received 40 kg/ha P_2O_5 as triple superphosphate.

Source: Garabet *et al*., 1995, as reported in FAO, 2001b.

Hussain *et al*. (2000) examined survey data collected during 1997-98 from 1 220 wheat-producing farms located in 14 canal commands in Sindh, Pakistan. They observed considerable variation in the amounts of inputs used by farmers and in the resulting wheat yields. The average number of irrigations per season ranged from 0.7 to 5.2 events on the various canal commands. Fertilizer use generally increased with the average number of irrigations, rising from 51 to 210 kg/ha of NPK. Land preparation costs also generally rose with the number of irrigations, suggesting that farmers located along canals with more frequent and reliable water deliveries are willing to invest more funds in advance of each season. This observation is also consistent with the notion that the availability of irrigation water enhances the marginal value product (MVP) of land in agriculture. The amount of seed used per hectare did not increase with the average number of irrigation events, but the average yield obtained did. In particular, average wheat yields increased through 3.5 irrigations per season and remained in a range of 1 600-2 300 kg/ha as irrigations increased to 4.3 events per season. Fertilizer use increased to about 170 kg/ha of NPK at 3.5 irrigations per season and remained in a range of 146-175 kg/ha of NPK while yields remained in a relatively narrow range. Wheat yields increased again when irrigations increased to 4.6 events per season and when fertilizer use exceeded 180 kg/ha of NPK. The summary data provided by Hussain *et al*. (2000) illustrate the complementary nature of fertilizer and irrigation water in wheat production. The estimated marginal product of irrigation water tends to decline with the increasing number of events per season. The decline is most dramatic as the average number of irrigations increases from 0.7 to 1.2 events per season. At higher numbers of irrigation events, the estimated marginal product increases again before declining to zero as the number of events approaches five per season. These observations suggest that farmers in Sindh would not be willing to pay for a fifth irrigation

TABLE 23

Fertilizer and water productivity in wheat production, Tel Hadya, Syria, year two, by irrigation treatment

Rainfall = 325 mm **Treatment**	**Grain yield** (kg/ha)	**Irrigation plus rainfall** (m^3/ha)	**Gross water use productivity** (kg/m^3)	**Gross fertilizer use productivity** (kg/kg)
Zero kg/ha N				
Rainfed	1 600	2 750	0.58	40.0
A: irrigated using 33% of the water applied to C	2 400	3 426	0.70	60.0
B: irrigated using 66% of the water applied to C	2 900	4 102	0.71	72.5
C: irrigated to field capacity during each irrigation event	3 200	4 780	0.67	80.0
50 kg/ha N				
Rainfed	1 700	2 750	0.62	18.9
A: irrigated using 33% of the water applied to C	3 200	3 426	0.93	35.6
B: irrigated using 66% of the water applied to C	3 800	4 102	0.93	42.2
C: irrigated to field capacity during each irrigation event	4 300	4 780	0.90	47.8
100 kg/ha N				
Rainfed	1 600	2 750	0.58	11.4
A: irrigated using 33% of the water applied to C	3 200	3 426	0.93	22.9
B: irrigated using 66% of the water applied to C	4 400	4 102	1.07	31.4
C: irrigated to field capacity during each irrigation event	4 600	4 780	0.96	32.9
150 kg/ha N				
Rainfed	600	2 750	0.22	3.2
A: irrigated using 33% of the water applied to C	2 900	3 426	0.85	15.3
B: irrigated using 66% of the water applied to C	4 000	4 102	0.98	21.0
C: irrigated to field capacity during each irrigation event	4 700	4 780	0.98	24.7

Note: All treatments, including N = 0 plots, received 40 kg/ha P_2O_5 as triple superphosphate.

Source: Garabet *et al.*, 1995, as reported in FAO, 2001b.

of wheat. The estimated marginal product of fertilizer is small but positive on all canal commands except the one where farmers receive an average of 0.7 irrigations per season. The marginal product ranges from 0.7 to 2.2 kg/ha on the other canals, with the exception of an unexplained spike of 7.7 kg/ha on one canal. In general, the estimated marginal product of fertilizer is independent of the number of irrigation events on the sample of farms examined.

Akhtar *et al.* (1988) collected field-level data from 150 randomly selected farmers in the Multan district of Punjab, Pakistan. Farmers with larger tracts of land and with access to a perennial canal irrigation system obtained higher wheat yields. Higher yielding fields were planted earlier and received a larger amount of phosphorus fertilizer (Table 25). More than half of the lower yielding wheat fields were planted after cotton, while most of the higher yielding fields were planted after fallow.

Maize

Maize yields in Syria generally respond well to irrigation water and nitrogen fertilizer, as Sharabi *et al.* (1982) demonstrated in a series of experiments in the lower Euphrates River basin. With no supplemental phosphorus, maize yields were substantially higher on plots receiving 150 kg/ha of nitrogen than on plots receiving only 80 kg/ha of nitrogen for four irrigation treatments (Table 26).

The incremental yield obtained by increasing the nitrogen application from 80 to 150 kg/ha was greatest with irrigations when soil moisture declined to 75 and 65 percent of field capacity. In these treatments, applying the additional 70 kg/ha of nitrogen doubled maize yields. The highest maize yield obtained without supplemental phosphorus fertilizer was 4 166 kg/ha.

TABLE 24

Fertilizer and water productivity in wheat production, Tel Hadya, Syria, year two, by nitrogen application

Rainfall = 325 mm **Treatment**	**Grain yield** (kg/ha)	**Irrigation plus rainfall** (m^3/ha)	**Gross water use productivity** (kg/m^3)	**Gross fertilizer use productivity** (kg/kg)
Rainfed				
Zero kg/ha N	1 600	2 750	0.58	40.0
50 kg/ha N	1 700	2 750	0.62	18.9
100 kg/ha N	1 600	2 750	0.58	11.4
150 kg/ha N	600	2 750	0.22	3.2
A: irrigated using 33% of the water applied to C				
Zero kg/ha N	2 400	3 426	0.70	60.0
50 kg/ha N	3 200	3 426	0.93	35.6
100 kg/ha N	3 200	3 426	0.93	22.9
150 kg/ha N	2 900	3 426	0.85	15.3
B: irrigated using 66% of the water applied to C				
Zero kg/ha N	2 900	4 102	0.71	72.5
50 kg/ha N	3 800	4 102	0.93	42.2
100 kg/ha N	4 400	4 102	1.07	31.4
150 kg/ha N	4 000	4 102	0.98	21.0
C: irrigated to field capacity during each irrigation event				
Zero kg/ha N	3 200	4 780	0.67	80.0
50 kg/ha N	4 300	4 780	0.90	47.8
100 kg/ha N	4 600	4 780	0.96	32.9
150 kg/ha N	4 700	4 780	0.98	24.7

Note: All treatments, including N = 0 plots, received 40 kg/ha P_2O_5 as triple superphosphate.

Source: Garabet *et al.*, 1995, as reported in FAO, 2001b.

TABLE 25

Wheat production practices in low and high-yielding fields, Multan district, Punjab, Pakistan, 1984-85

Item	**Low-yielding fields (< 1 840 kg/ha)**	**High-yielding fields (> 2 640 kg/ha)**
Average wheat yield (kg/ha)	1 517	3 149
Average farm size (ha)	6	10
Wheat after cotton (%)	63	22
New varieties planted (%)	16	19
Certified seed (%)	6	22
Planted after December (%)	72	59
Average irrigations	6	7
Average N applied (kg/ha):		
Basal dose	29	30
Top dressing	70	64
Average P applied (kg/ha)	48	68
Fields with broadleaf weeds (%)	19	6

Source: Akhtar *et al.*, 1988.

Adding 120 kg/ha of phosphorous fertilizer before planting maize improved the yield on some treatments, while not affecting yields on others (Table 27). For example, there was little impact on maize yields with irrigations at a soil moisture of 85 percent of field capacity. However, yields improved on the plots receiving 80 and 200 kg/ha of nitrogen with irrigations at 75 percent of field capacity. Results on other plots were mixed.

TABLE 26

Fertilizer and water productivity in maize production, lower Euphrates River basin, Syria, 1982, no supplemental P_2O_5

Treatment	Yield (kg/ha)	Evapotranspiration (m³/ha)	Average product of water (ET_a) (kg/m³)	Average product of fertilizer (kg/kg)
Irrigation at 85% of field capacity				
80 kg/ha N	2 690	5 968	0.45	30.0
150 kg/ha N	3 238	5 968	0.54	20.2
200 kg/ha N	3 595	5 968	0.60	17.1
Irrigation at 75% of field capacity				
80 kg/ha N	2 119	5 245	0.40	23.5
150 kg/ha N	4 166	5 245	0.79	26.0
200 kg/ha N	3 405	5 245	0.65	16.4
Irrigation at 65% of field capacity				
80 kg/ha N	1 547	4 697	0.33	17.2
150 kg/ha N	3 405	4 697	0.72	21.3
200 kg/ha N	2 428	4 697	0.52	11.6
Irrigation at 55% of field capacity				
80 kg/ha N	2 000	3 763	0.53	22.2
150 kg/ha N	2 405	3 763	0.64	15.0
200 kg/ha N	1 738	3 763	0.46	8.3

Notes: All treatments received no phosphorus fertilizer and 10 kg/ha K_2O. Nitrogen and potassium fertilizers applied in two events: two-thirds of the nitrogen and one-third of the potassium at three leaves; the remainder at tasselling. Irrigations applied using farmers' traditional methods when soil moisture content reached 85, 75, 65 or 55% of field capacity.

Source: Sharabi *et al.*, 1982, as reported in FAO, 2001b.

TABLE 27

Fertilizer and water productivity in maize production, lower Euphrates River basin, Syria, 1982, 120 kg/ha P_2O_5

Treatment	Yield (kg/ha)	Evapotranspiration (m³/ha)	Average product of water (ET_a) (kg/m³)	Average product of fertilizer (kg/kg)
Irrigation at 85% of field capacity				
80 kg/ha N	2 428	5 968	0.41	11.6
150 kg/ha N	3 509	5 968	0.59	12.5
200 kg/ha N	3 524	5 968	0.59	10.7
Irrigation at 75% of field capacity				
80 kg/ha N	4 143	5 245	0.79	19.7
150 kg/ha N	4 105	5 245	0.78	14.7
200 kg/ha N	4 119	5 245	0.78	12.5
Irrigation at 65% of field capacity				
80 kg/ha N	2 714	4 697	0.58	12.9
150 kg/ha N	1 285	4 697	0.27	4.6
200 kg/ha N	2 643	4 697	0.56	8.0
Irrigation at 55% of field capacity				
80 kg/ha N	1 690	3 763	0.45	8.0
150 kg/ha N	2 071	3 763	0.55	7.4
200 kg/ha N	3 762	3 763	1.00	11.4

Notes: All treatments received 120 kg/ha P_2O_5 and 10 kg/ha K_20. Phosphorus fertilizer applied before planting. Nitrogen and potassium fertilizers applied in two events: two-thirds of the nitrogen and one-third of the potassium at three leaves; the remainder at tasselling. Irrigations applied using farmers' traditional methods when soil moisture content reached 85, 75, 65 or 55% of field capacity.

Source: Sharabi *et al.*, 1982, as reported in FAO, 2001b.

TABLE 28

Fertilizer and water productivity in maize production, lower Euphrates River basin, Syria, 1982, 200 kg/ha P_2O_5

Treatment	Yield (kg/ha)	Evapotranspiration (m^3/ha)	Average product of water (ET_a) (kg/m^3)	Average product of fertilizer (kg/kg)
Irrigation at 85% of field capacity				
80 kg/ha N	2 809	5 968	0.47	9.7
150 kg/ha N	2 428	5 968	0.41	6.7
200 kg/ha N	3 905	5 968	0.65	9.5
Irrigation at 75% of field capacity				
80 kg/ha N	4 405	5 245	0.84	15.2
150 kg/ha N	2 952	5 245	0.56	8.2
200 kg/ha N	1 928	5 245	0.37	4.7
Irrigation at 65% of field capacity				
80 kg/ha N	2 381	4 697	0.51	8.2
150 kg/ha N	1 952	4 697	0.42	5.4
200 kg/ha N	1 857	4 697	0.39	4.5
Irrigation at 55% of field capacity				
80 kg/ha N	1 071	3 763	0.28	3.7
150 kg/ha N	2 643	3 763	0.70	7.3
200 kg/ha N	2 024	3 763	0.54	4.9

Notes: All treatments received 200 kg/ha P_2O_5 and 10 kg/ha K_20. Phosphorus fertilizer applied before planting. Nitrogen and potassium fertilizers applied in two events: two-thirds of the nitrogen and one-third of the potassium at three leaves; the remainder at tasselling. Irrigations applied using farmers' traditional methods when soil moisture content reached 85, 75, 65 or 55% of field capacity.

Source: Sharabi *et al.*, 1982, as reported in FAO, 2001b.

Similarly, plots receiving 200 kg/ha of phosphorous fertilizer yielded mixed results. The additional phosphorus had little impact on most treatments, but it did generate a higher yield on the plot receiving 80 kg/ha of nitrogen with irrigations at a soil moisture of 75 percent of field capacity (Table 28). Dividing maize yield by crop evapotranspiration provides an estimate of the average productivity of water. These estimates range from 0.27 kg/m^3 on a plot receiving 150 kg/ha of nitrogen and 120 kg/ha of phosphorous to 1.00 kg/m^3 on a plot receiving 200 kg/ha of nitrogen and 120 kg/ha of phosphorous. In general, the plots irrigated at a soil moisture of 75 percent of field capacity generated higher estimates of water use productivity than plots irrigated at other frequencies. Similarly, the highest estimates of fertilizer use productivity, calculated by dividing maize yield by the sum of the weights of the three fertilizers applied, are generally higher on the plots irrigated at a soil moisture of 75 percent of field capacity. In general, the data provided by Sharabi *et al.* (1982) suggest that the additional irrigation water required to irrigate at 85 percent rather than 75 percent of field capacity may not be worth the additional cost. Similarly, the incremental yield obtained by increasing the phosphorus application from 120 to 200 kg/ha may not be sufficient to justify the additional cost.

Sugar beet

Khalifa *et al.* (1994) examined the impact of nitrogen fertilizer and irrigation frequency on sugar-beet yields during three seasons in the lower Euphrates River basin, Syria. In 1987, increasing applications of nitrogen fertilizer generated higher yields of roots and sugar (Table 29). With a nitrogen application of 240 kg/ha of, sugar yields exceeded 10 000 kg/ha with each irrigation treatment. With a nitrogen applications of 120 kg/ha, the average yield was 9 467 kg/ha on plots that received irrigation whenever soil moisture declined to 85 percent of field capacity. The average productivity of irrigation water increased with higher rates of nitrogen within each irrigation treatment, rising from about 0.50 kg/m^3 with no supplemental nitrogen to more

TABLE 29

Sugar-beet yields and water and fertilizer productivity, lower Euphrates River basin, Syria, 1987, autumn planting

Irrigation treatment	Crop yield		Average product of applied water		Average product of fertilizer	
	Roots (kg/ha)	Sugar (kg/ha)	Roots (kg/m^3)	Sugar (kg/m^3)	Roots (kg/kg)	Sugar (kg/kg)
Irrigation at 85% of field capacity						
Zero kg/ha N	28 889	5 049	2.96	0.52	120.4	21.0
120 kg/ha N	68 148	9 467	6.99	0.97	189.3	26.3
240 kg/ha N	72 593	11 968	7.44	1.23	151.2	24.9
Irrigation at 75% of field capacity						
Zero kg/ha N	24 815	4 442	3.12	0.56	103.4	18.5
120 kg/ha N	41 481	6 204	5.22	0.78	115.2	17.2
240 kg/ha N	81 481	12 918	10.25	1.62	169.7	26.9
Irrigated at 65% of field capacity						
Zero kg/ha N	22 963	3 267	3.44	0.49	95.7	13.9
120 kg/ha N	39 299	6 775	5.88	1.01	109.0	18.8
240 kg/ha N	70 370	10 975	10.55	1.64	146.6	22.9

Notes: Nitrogen applied as ammonium nitrate on all plots receiving nitrogen. All treatments, including N = 0 plots, received 120 kg/ha P_2O_5 as triple superphosphate and 120 kg/ha K_2O as potassium sulphate. The irrigation treatments received 17, 13 and 10 irrigations resulting in total water applications of 11 200, 9 050, and 7 580 m^3/ha respectively.

Source: Khalifa *et al.*, 1994, as reported in FAO, 2001b.

than 1.6 kg/m^3 with 240 kg/ha of nitrogen. The impact of irrigation water on fertilizer productivity is evident on the plots receiving zero and 120 kg/ha of supplemental nitrogen. In particular, the average productivity of fertilizer increased from 13.9 to 21.0 kg of sugar per kilogram of fertilizer as irrigation frequency increased on the plots receiving zero supplemental nitrogen. Similarly, the average productivity of fertilizer increased from 18.8 to 26.3 kg/kg as irrigation frequency increased on plots receiving 120 kg/ha of nitrogen.

Khalifa *et al.* (1994) examined the efficiency of nitrogen use by sugar-beet plants in the second year of their experiment. In particular, they examined how the plants utilize nitrogen from the ammonium and nitrate components of ammonium nitrate. For the purpose of this study, the data generated by Khalifa *et al.* (1994) provide additional observations regarding the average and incremental productivity of irrigation water and fertilizer. In general, the application of 120 kg/ha of nitrogen provided a substantial increase in average yield in all of the irrigation treatments (Table 30). The application of nitrogen enhanced the estimated average productivity of water, and increases in irrigation frequency enhanced the average productivity of fertilizer. The nitrogen fertilizer use efficiencies (with respect to nitrate) determined in the experiment were 24.5, 28.0 and 14.1 percent for the 85, 75 and 65-percent irrigation treatments. The nitrogen use efficiencies for ammonium were 59.8, 53.8 and 50.8 percent (FAO, 2001b). The goal in year three of the experiments was to examine the yield response to 120 kg/ha of nitrogen applied as either ammonium sulphate or urea in three irrigation treatments. In all treatments, nitrogen applied in either form resulted in substantial increases in sugar-beet yields compared with plots receiving no supplemental nitrogen (Table 31). The yield response to urea was somewhat stronger than the response to ammonium sulphate on plots irrigated at a soil moisture level of 85 percent of field capacity. Ammonium sulphate generated the greater yield response when irrigations occurred at 75 and 65 percent of field capacity. Applications of nitrogen using either source enhanced the average productivity of irrigation water.

The Directorate of Agricultural Research has examined the role of boron, potassium and manganese in sugar-beet production in a series of experiments conducted at several stations in

TABLE 30

Sugar-beet yields and water and fertilizer productivity, lower Euphrates River basin, Syria, 1988, spring planting

Irrigation treatment	**Crop yield**		**Average product of applied water**		**Average product of fertilizer**	
	Roots (kg/ha)	**Sugar** (kg/ha)	**Roots** (kg/m^3)	**Sugar** (kg/m^3)	**Roots** (kg/kg)	**Sugar** (kg/kg)
Irrigation at 85% of field capacity						
Zero kg/ha N	14 329	2 475	1.72	0.30	59.7	10.3
120 kg/ha N (NO_3^*)	52 007	4 874	6.24	0.58	144.5	13.5
120 kg/ha N (NH_4^*)	39 817	5 781	4.78	0.69	110.6	16.1
Irrigation at 75% of field capacity						
Zero kg/ha N	16 720	3 114	5.50	0.43	69.7	13.0
120 kg/ha N (NO_3^*)	44 707	4 137	6.17	0.57	124.2	11.5
120 kg/ha N (NH_4^*)	35 873	5 528	4.95	0.76	99.6	15.4
Irrigated at 65% of field capacity						
Zero kg/ha N	11 344	2 149	1.81	0.34	47.3	8.9
120 kg/ha N (NO_3^*)	23 767	3 496	3.80	0.56	66.0	9.7
120 kg/ha N (NH_4^*)	33 500	3 207	5.35	0.51	93.1	8.9

Notes: The goal of the experiment was to estimate the efficiency with which sugar-beet plants use the ammonium and nitrate forms of nitrogen. Nitrogen applied as ammonium nitrate on all plots receiving nitrogen. On some plots, the nitrate was labelled (NO_3^*), while on other plots the ammonium was labelled (NH_4^*) to allow monitoring of nitrogen uptake.

Source: Khalifa *et al.*, 1994, as reported in FAO, 2001b.

TABLE 31

Sugar-beet yields and water and fertilizer productivity, lower Euphrates River basin, Syria, 1989, spring planting

Irrigation treatment	**Crop yield**		**Average product of applied water**		**Average product of fertilizer**	
	Roots (kg/ha)	**Sugar** (kg/ha)	**Roots** (kg/m^3)	**Sugar** (kg/m^3)	**Roots** (kg/kg)	**Sugar** (kg/kg)
Irrigation at 85% of field capacity						
Zero kg/ha N	15 100	1 683	1.84	0.20	63.0	7.0
120 kg/ha N as AS	27 500	3 088	3.35	0.38	76.4	8.6
120 kg/ha N as urea	28 670	3 388	3.49	0.41	79.6	9.4
Irrigation at 75% of field capacity						
Zero kg/ha N	16 300	1 894	2.28	0.26	67.9	7.9
120 kg/ha N as AS	28 470	3 484	3.98	0.49	79.1	9.7
120 kg/ha N as urea	28 500	3 168	3.99	0.44	79.2	8.8
Irrigated at 65% of field capacity						
Zero kg/ha N	17 500	2 032	2.88	0.33	72.9	8.5
120 kg/ha N as AS	35 670	4 252	5.87	0.70	99.1	11.8
120 kg/ha N as urea	27 830	3 381	4.58	0.56	77.3	9.4

Notes: The goal of this experiment was to monitor the yield response to nitrogen applied as ammonium sulphate (AS) or urea.

Source: Khalifa *et al.*, 1994, as reported in FAO, 2001b.

Syria. Some of the data generated in these studies do not depict significant differences in sugar-beet yields or average products, but they do provide information regarding the potential yields of sugar beets in several key production regions (FAO, 2001b). For example, sugar yields achieved at the Ghab station in 1998 exceeded 11 000 kg/ha, while sugar yields obtained at the Deir Al-Zoor station were less than 7 000 kg/ha (Table 32). Sugar yields achieved at the Hama and Rakka stations ranged from 8 000 to 10 000 kg/ha. The estimated average products of fertilizer use were also highest at the Ghab station in 1998.

Data generated in 1999 depict a different pattern regarding relative sugar-beet yields at various experiment stations. In particular, sugar yields were lowest at the Ghab station and highest at the Rakka, Deir Al-Zoor and Homs stations (Table 33). It is possible that the data presented in Table 33 represent spring-planted sugar-beet yields and these yields may be much smaller than autumn-planted yields in Syria, where high summer temperatures may limit sugar-beet yield potential. Adding boron and manganese in the fertilizer programme can enhance sugar-beet root and sugar yields.

TABLE 32

Impact of potassium on sugar-beet yields and fertilizer productivity, experiment stations, Syria, 1998

Station	Treatment	Root yield (kg/ha)	Sugar yield (kg/ha)	Average product of fertilizer Roots (kg/kg)	 Sugar (kg/kg)
Hama	N, P	69 580	9 700	231.9	32.3
	N, P, K	66 670	8 610	158.7	20.5
	N, P, K + 120 kg/ha K_20	71 880	9 480	133.1	17.6
Ghab	N, P	81 070	11 970	170.2	39.9
	N, P, K	82 500	13 440	196.4	32.0
	N, P, K + 120 kg/ha K_20	80 710	12 250	149.5	22.7
Rakka	N, P	61 070	8 700	203.6	29.0
	N, P, K	61 250	8 850	145.8	21.6
	N, P, K + 120 kg/ha K_20	53 030	7 890	98.2	14.6
Deir	N, P	51 610	6 660	172.0	22.2
Al-Zoor	N, P, K	51 780	6 430	123.3	15.4
	N, P, K + 120 kg/ha K_20	51 790	5 510	95.9	10.2

Notes: All treatments received 120 kg/ha of P_2O_5 as triple superphosphate, and some treatments received 120 kg/ha K_2O as potassium sulphate. Autumn-planted cultivars received 180 kg/ha N as urea, while winter and spring-planted cultivars received 160 kg/ha N as urea.

Source: DIWU-MAAR, 1999, as reported in FAO, 2001b.

TABLE 33

Impact of potassium on sugar-beet yields and fertilizer productivity, experiment stations, Syria, 1999

Station	Treatment	Root yield (kg/ha)	Sugar yield (kg/ha)	Average product of fertilizer Roots (kg/kg)	 Sugar (kg/kg)
Hama	N, P	38 940	4 600	129.8	15.3
	N, P, K	52 590	5 780	125.2	13.8
	N, P, K + 120 kg/ha K_20	38 200	4 440	70.8	8.2
Ghab	N, P	26 490	3 030	88.3	10.1
	N, P, K	26 960	3 810	64.2	9.1
	N, P, K + 120 kg/ha K_20	24 640	3 660	45.6	6.8
Rakka	N, P	54 170	7 220	180.6	24.1
	N, P, K	48 210	5 520	114.7	13.1
	N, P, K + 120 kg/ha K_20	52 020	5 580	96.3	10.3
Deir	N, P	49 050	6 060	163.5	20.2
Al-Zoor	N, P, K	51 790	6 290	123.3	15.0
	N, P, K + 120 kg/ha K_20	53 570	6 650	99.2	12.3
Homs	N, P	44 450	4 470	148.2	14.9
	N, P, K	53 780	5 810	128.0	13.8
	N, P, K + 120 kg/ha K_20	47 330	5 380	87.6	10.0

Notes: All treatments received 120 kg/ha of P_2O_5 as triple superphosphate, and some treatments received 120 kg/ha K_2O as potassium sulphate. Autumn-planted cultivars received 180 kg/ha N as urea, while winter and spring planted cultivars received 160 kg/ha N as urea.

Source: DIWU-MAAR, 2000, as reported in FAO, 2001b.

TABLE 34

Impact of boron and manganese on sugar-beet yields, autumn planting, Ghab experiment station, Syria, 1999-2000

Station	Treatment	Root yield	Sugar yield	Average product of fertilizer	
				Roots	Sugar
		(kg/ha)	(kg/ha)	(kg/kg)	(kg/kg)
Ghab	N, P, K	77 380 ^{C}	9 080 ^{B}	175.8	20.6
	N, P, K + 5 kg/ha borax	84 500 ^{B}	10 380 ^{A}	189.9	23.3
	N, P, K + 10 kg/ha borax	88 200 $^{A\,B}$	11 550 ^{A}	196.0	25.7
	N, P, K + 5 kg/ha $MnSO_4$	86 400 $^{A\,B}$	11 180 ^{A}	194.2	25.1
	N, P, K + 5 kg/ha borax + 5 kg/ha $MnSO_4$	91 070 ^{A}	10 250 ^{A}	202.4	22.8

Notes: All treatments received 120 kg/ha of P_2O_5 as triple superphosphate, 120 kg/ha K_2O as potassium sulphate, and 180 kg/ha N as urea. Results distinguished by one superscript differ from those distinguished by another superscript by a statistically different amount.

Source: DIWU-MAAR, 2001, as reported in FAO, 2001b.

A recent experiment at the Ghab experiment station produced significant treatment effects. The addition of 5 kg/ha of borax or 5 kg/ha of manganese sulphate increased root yields of autumn-planted sugar beets significantly (Table 34). A combination of borax and manganese sulphate produced the highest root yield (91 070 kg/ha). Application of 5 kg/ha of borax, 5 kg/ha of manganese sulphate, or a combination of the two materials also increased sugar yields significantly.

Sugar beets have relatively high requirements for both water and fertilizer. The recommended NPK fertilizer applications for autumn-planted sugar beets in Syria are 180, 120 and 120 kg/ha respectively (FAO, 2001b). The nitrogen recommendation for winter and spring-planted sugar beets is 160 kg/ha. Sugar beets generally receive irrigation 6-10 times per season at rates of 800 m^3/ha with surface irrigation, or 300 m^3/ha with sprinklers. Achieving the optimal balance

TABLE 35

Water and fertilizer productivity, small basins of sugar beets, lower Euphrates River basin, Syria, 1981 and 1982

Season and treatment	Irrigation plus rainfall	Crop yield	Average products of water and fertilizer with regard to root yield	
			Water	Fertilizer
	(m^3/ha)	(kg/ha)	(kg/m^3)	(kg/kg)
1981 Season (rainfall = 130 mm)				
Irrigate to field capacity when soil moisture declines to:				
85% of field capacity	7 734	59 800	7.73	124.58
75% of field capacity	7 884	54 500	6.91	111.68
65% of field capacity	7 574	47 650	6.29	97.64
55% of field capacity	6 304	40 900	6.49	83.81
1982 Season (rainfall = 48 mm)				
Irrigate to field capacity when soil moisture declines to:				
85% of field capacity	4 606	46 400	10.07	95.08
75% of field capacity	4 176	38 800	9.29	75.51
65% of field capacity	2 884	19 000	6.59	38.93
55% of field capacity	2 884	11 000	3.81	22.54

Note: All treatments in both years received: (i) 138 kg/ha of P_2O_5 as triple superphosphate before planting; (ii) 67 kg/ha N as ammonium nitrate and 75 kg/ha K_2O as potassium sulphate at 10 days after planting; (iii) 67 kg/ha N as ammonium nitrate and 75 kg/ha K_2O as potassium sulphate at 45 days after planting; and (iv) 67 kg/ha N as ammonium nitrate at 75 days after planting.

Source: ACSAD, 1981 and 1982, as reported in FAO, 2001b.

between vegetative growth and sugar content in the roots requires careful management of both irrigation water and fertilizer. Early work with sugar beets in the lower Euphrates River basin demonstrates the relationship between applied water and crop yield. A study examined the effect of four irrigation treatments on well-fertilized plots of sugar beets in order to determine the average and incremental productivity of irrigation water in 1981 and 1982 (ACSAD, 1981, 1982). Plots received irrigation to restore soil moisture to field capacity when soil moisture declined to 85, 75, 65 and 55 percent of field capacity (Table 35). In both years, yields were higher on the plots irrigated more frequently. In 1981, the plots received 130 mm of rainfall and the average yield on plots irrigated when soil moisture declined to 55 percent of field capacity was 40 900 kg/ha. Increasing the frequency of irrigation resulted in average yields as high as 59 800 kg/ha. In 1982, the rainfall was lower and the average yields ranged from 11 000 kg/ha on the driest treatments to 46 400 kg/ha on plots irrigated when soil moisture declined to 85 percent of field capacity. In both years, the average productivity of fertilizer increased substantially with the volume of applied water (all treatments received the same amount of fertilizer.

Cotton

Sharabi *et al*. (1982) examined the relationship between cotton yields and irrigation on small basins in the lower Euphrates River basin, Syria (FAO, 2001b). Cotton yields increased monotonically with irrigation frequency, but average water use efficiency rose and then declined as irrigation frequency increased (Table 36). In particular, seed cotton yields exceeded 4 tonnes/ha on plots irrigated when soil moisture in the top 30-45 cm of soil declined to 75-85 percent of field capacity. The average yields were 3.9 and 3.6 tonnes/ha when irrigations occurred at soil moisture levels of 65 and 55 percent of field capacity respectively. The highest estimated water use efficiency, defined as crop yield divided by evapotranspiration, occurred with irrigation at a soil moisture level of 65 percent of field capacity. Crop yields with all treatments were substantially larger than the average yield obtained in Syria in 1982 (2.7 kg/ha). This was due in part to the heavy application of supplemental fertilizer.

Laser levelling of agricultural fields can generate higher irrigation efficiencies and higher crop yields by improving the uniformity of water deliveries where farmers use surface irrigation methods. Farmers may level fields to zero slope in order to enhance basin irrigation or to a small, positive slope in order to enhance irrigation with furrows or bordered checks. Laser levelling is in extensive use in the western United States as a means of reducing water deliveries and improving crop yields. The procedure may also be helpful in Syria and other countries where most farmers use surface irrigation methods. Sawmi *et al*. (2001) examined the potential

TABLE 36

Irrigation and water use efficiency, small basins of cotton, lower Euphrates River basin, Syria, 1982

	Applied water and change in soil moisture (m^3/ha)	**Crop yield** (kg/ha)	**Evapotranspiration** (m^3/ha)	**Water use efficiency** (kg/m^3)
Irrigate to field capacity when soil moisture declines to:				
85% of field capacity	14 811	4 181	8 226	0.508
75% of field capacity	13 625	4 175	8 122	0.515
65% of field capacity	12 127	3 931	7 224	0.544
55% of field capacity	11 288	3 575	6 947	0.515

Note: All treatments received 400 kg/ha of triple superphosphate (46%) at planting, 200 kg/ha of ammonium nitrate (35%) and 100 kg/ha of potassium sulphate at thinning, and 200 kg/ha of ammonium nitrate (35%) and 100 kg/ha of potassium sulphate at flowering.

Source: Sharabi *et al*., 1982, as reported in FAO, 2001b.

TABLE 37

Water and fertilizer productivity with laser-levelling, cotton plots, four provinces, Syria, 1992-99

Province and irrigation method	**Applied water** (m^3/ha)	**Crop yield** (kg/ha)	**Average product ofapplied water** (kg/m^3)	**Average product of fertilizer** (kg/kg)
Aleppo				
Levelled	8 145	4 533	0.56	17.9
Not levelled	10 380	3 528	0.35	14.0
Hasaka				
Levelled	13 499	3 247	0.25	18.9
Not levelled	19 125	2 687	0.15	10.7
Deir Al-Zoor				
Levelled	12 205	3 716	0.31	16.4
Not levelled	15 851	2 822	0.17	12.5
Hama				
Levelled	8 597	4 310	0.51	17.1
Not levelled	12 495	3 739	0.31	14.8
Average				
Levelled	10 612	3 952	0.41	16.9
Not levelled	14 463	3 194	0.25	13.0

Note: Treatments in Aleppo, Hasaka, and Hama received 190 kg/ha of nitrogen as urea and 62 kg/ha of P_2O_5 as triple superphosphate. Treatments in Deir Al-Zoor received 180 kg/ha of nitrogen as urea and 46 kg/ha of P_2O_5 as triple superphosphate.

Source: Sawmi *et al.*, 2001, as reported in FAO, 2001b.

farm-level gains of laser levelling for cotton yields in four Syrian provinces. Their results suggest that laser levelling can enhance crop yields and the average productivity of water and fertilizer. The average increases in cotton yield achieved with laser levelling ranged from 560 to 1 005 kg/ha, with an average increase of 758 kg/ha in the four provinces (Table 37). The average reductions in water applications ranged from 2 235 to 5 626 m^3/ha, with an average reduction of 3 851 m^3/ha in the four provinces. On average, compared with unlevelled plots, laser levelling increased cotton yields by 19 percent and reduced water applications by 27 percent. Estimates of the average productivity of water and fertilizer are 64 and 30 percent higher on laser-levelled plots.

WATER CONSERVATION AND IMPROVED IRRIGATION STUDIES

Sarwar and Bastiaanssen (2001) compared farm-level irrigation practices and crop yields with those that would reflect a water conservation strategy in the Fourth Drainage Project in Punjab, Pakistan. A shallow, saline water table underlies much of the study area, causing a reduction in the potential yields of cotton, wheat and maize. Most farmers irrigate according to the availability of water in the canal system, while some farmers supplement their surface water supply with groundwater from tubewells. Simulation results suggest that farmers can improve the average productivity of water by reducing the volume of water applied and by scheduling irrigations to match crop water requirements and to account for contributions from the shallow water table. The estimated yields obtained in a water conservation scenario are lower than those obtained with farmers' irrigation practices, but several measures of average productivity are higher in the water conservation scenario. For example, the wheat yield obtained using farmers' irrigation practices is 3.34 tonnes/ha, while that obtained in the water conservation scenario is 3.07 tonnes/ha (Table 38). However, farmers' irrigation practices entail the application of 325 mm of irrigation water compared with 195 mm in the water conservation scenario. As a result, the estimated average productivities of irrigation water are 1.03 and 1.57 kg/m^3 respectively. Similarly, the estimated average productivities of irrigation water for cotton are 0.60 and 0.72 kg/m^3

TABLE 38

Water productivities and drainage depths for a water conservation strategy, Fourth Drainage Project, Punjab, Pakistan

	Water conservation scenario		**Farmers' practices**	
Parameter	**Wheat**	**Cotton**	**Wheat**	**Cotton**
Precipitation (mm)	106	270	106	270
Irrigation depth (mm)	195	260	325	325
Actual Transpiration (mm)	327	524	353	541
Actual evaporation (mm)	54	109	50	177
Actual evapotranspiration (mm)	381	633	403	718
Drainage depth (mm)	5	15	28	126
Estimated yield (kg/ha)	3 070	1 880	3 340	1 940
Average productivity of irrigation water (kg/m^3)	1.57	0.72	1.03	0.60

Source: Sarwar and Bastiaanssen, 2001.

respectively. Implementing the water conservation strategy would improve the average productivity of irrigation water in the near term and reduce pressure from the shallow, saline water table in the long term. The water table would rise more slowly and might recede with reductions in deep percolation. The average depths of drainage water using the farmers' irrigation practices are 28 and 126 mm for wheat and cotton, while the corresponding values in the water conservation scenario are 5 and 15 mm. Hence, the shallow groundwater would receive less water and salt each year if farmers were able and willing to implement the water conservation strategy.

The Directorate of Irrigation and Water Uses in the Ministry of Agriculture and Agrarian Reform has examined the impact of alternative irrigation methods on sugar-beet yields and water and fertilizer productivity at several locations in Syria. Studies conducted at the Tezeen research station compared sprinkler irrigation with syphon-tube irrigation of long strips ranging from 100 to 140 m in length (DIWU-MAAR, 2000). The volume of applied water was smallest on the sprinkler-irrigated plots and it increased with increasing strip length on the plots irrigated with syphon tubes (Table 39). Sugar yields averaged 9 847 kg/ha on the sprinkler-irrigated plots, while average sugar yields on the syphon-tube treatments ranged from 5 971 to 6 686 kg/ha. The average products of applied water with respect to sugar production ranged from 0.55 to 0.61 kg/m^3 for the syphon-tube-irrigated strips, while the average product of applied water on the sprinkler-irrigated plots was 1.73 kg/m^3. The estimated average products of fertilizer with respect to root and sugar production were also much higher for the sprinkler-irrigated treatment.

TABLE 39

Water and fertilizer productivity with strip and sprinkler irrigation, sugar beet, Tezeen Station, Syria, 2000

Irrigation treatment	**Applied water**	**Crop yield**		**Average product of applied water**		**Average product of fertilizer**	
		Roots	**Sugar**	**Roots**	**Sugar**	**Roots**	**Sugar**
	(m^3/ha)	(kg/ha)	(kg/ha)	(kg/m^3)	(kg/m^3)	(kg/kg)	(kg/kg)
Strips (100 m)	9 739	52 760	5 971	5.4	0.61	114.7	13.0
Strips (120 m)	11 017	55 020	6 461	5.0	0.59	119.6	14.0
Strips (140 m)	12 176	55 550	6 686	4.6	0.55	120.8	14.5
Sprinklers	5 677	77 770	9 847	13.7	1.73	169.1	21.4

Notes: All treatments received 220 kg/ha N as urea, 120 kg/ha P_2O_5 as triple superphosphate, and 120 kg/ha K_2O. Phosphorus and potassium fertilizers applied before planting. Nitrogen applications: half with the first irrigation; and half after thinning.

The estimated irrigation efficiencies (ET_a/applied water) for the four treatments in the order of appearance in the table are: 0.51, 0.46, 0.42 and 0.91.

Source: DIWU-MAAR, 2000, as reported in FAO, 2001b.

TABLE 40

Water and fertilizer productivity with different irrigation methods, sugar beet, Al-Mreiya Station, Syria, 2000

Irrigation treatment	Applied water	Crop yield		Average product of applied water		Average product of fertilizer	
		Roots	**Sugar**	**Roots**	**Sugar**	**Roots**	**Sugar**
	(m^3/ha)	(kg/ha)	(kg/ha)	(kg/m^3)	(kg/m^3)	(kg/kg)	(kg/kg)
Bi-wall (10 cm)	8 413	60 500	6 660	7.2	0.79	131.5	14.5
Bi-wall (30 m)	8 350	61 500	7 050	7.4	0.84	133.7	15.3
In-line (40 cm)	8 354	63 000	7 060	7.5	0.85	137.0	15.4
Sprinklers	10 940	52 000	5 700	4.8	0.52	113.0	12.4
Strips (150 m)	12 756	51 000	5 900	4.0	0.46	110.9	12.8
Farmer's basin	16 553	43 000	4 180	2.0	0.25	93.5	9.1

Notes: All treatments received 220 kg/ha N as urea, 120 kg/ha P_2O_5 as triple superphosphate, and 120 kg/ha K_2O. Phosphorus and potassium fertilizers applied before planting. Nitrogen applications: half with the first irrigation; and half after thinning.

The estimated irrigation efficiencies (ET_a/applied water) for the six treatments in the order of appearance in the table are: 0.96, 0.96, 0.95, 0.74, 0.65 and 0.50.

Source: DIWU-MAAR, 2000, as reported in FAO, 2001b.

The Directorate of Irrigation and Water Uses conducted a similar study at the Al-Mreiya research station in Deir Al-Zoor. This study included three drip-irrigation treatments and a treatment using the farmers' traditional basin method of irrigation. The volumes of water applied were smallest on the drip-irrigated plots and highest for the farmers' basin treatment (Table 40). Root and sugar yields were highest on the drip-irrigated plots and lowest on the basin-irrigated plots. The estimated higher average products of applied water and fertilizer on the drip-irrigated plots reflect the higher irrigation efficiencies and sugar yields achieved with those systems. The sugar yields obtained on the strip and sprinkler-irrigated plots were similar, but the strip-irrigated plots received an additional 1 800 m^3/ha of water. Table 41 presents summary data describing a similar comparison of irrigation systems at the Al-Mukhtariet research station in Homs. The average volume of water applied was again smallest on the drip-irrigated plots, while the largest average volume occurred on the strip-irrigated plots. Irrigation efficiencies ranged from 53 percent on the strip-irrigated plots to 90 percent on the drip-irrigated plots. The average sugar yield achieved with drip irrigation was 27 percent greater than the average sugar yield obtained with sprinklers and more than double the average yield obtained using basin irrigation. As a result, the estimated average products of applied water and fertilizer are substantially larger for the drip system than for the other irrigation methods.

TABLE 41

Water and fertilizer productivity with different irrigation methods, sugar beet, Al Mukhtariet Station, Syria, 2000

Irrigation treatment	Applied water	Crop yield		Average product of applied water		Average product of fertilizer	
		Roots	**Sugar**	**Roots**	**Sugar**	**Roots**	**Sugar**
	(m^3/ha)	(kg/ha)	(kg/ha)	(kg/m^3)	(kg/m^3)	(kg/kg)	(kg/kg)
Drip	6 253	60 500	8 806	9.7	1.41	130.1	18.9
Sprinklers	7 150	48 917	6 928	6.8	0.97	105.2	14.9
Strips (100 m)	12 036	46 250	6 684	3.8	0.56	99.5	14.4
Farmer's basin	8 965	32 750	4 245	3.7	0.47	70.4	9.1

Notes: All treatments received 120 kg/ha N as urea, 120 kg/ha P_2O_5 as triple superphosphate, and 120 kg/ha K_2O. Phosphorus and potassium fertilizers applied before planting. Nitrogen applications: half with the first irrigation; and half after thinning. All treatments irrigated when soil moisture content reached 75 percent of field capacity. Data are average values of treatments receiving 150, 200 and 250 kg/ha of nitrogen.

The estimated irrigation efficiencies (ET_a/applied water) for the four treatments in the order of appearance in the table are: 0.90, 0.87, 0.53 and 0.62.

Source: DIWU-MAAR, as reported in FAO, 2001b.

TABLE 42

Water and fertilizer productivity with basin, sprinkler and drip systems, cotton plots, Syria, 1991-95

Irrigation method	**Applied water** (m³/ha)	**Crop yield** (kg/ha)	**Average product of applied water** (kg/m³)	**Average product of fertilizer** (kg/kg)
Basin irrigation	14 362	3 240	0.23	13.4
Sprinkler irrigation	10 622	4 370	0.41	18.1
Drip irrigation	6 460	4 589	0.71	19.0

Note: Treatments received 186 kg/ha of N as urea and 55 kg/ha of P_2O_5 as triple superphosphate.

Source: Sawmi *et al.*, 2000, as reported in FAO, 2001b.

The experiment station studies describe a wide range of root and sugar yields for autumn and spring-planted sugar beets in various locations in Syria. The results also describe the potential for increasing sugar-beet yields substantially by applying supplemental nitrogen and phosphorus and by improving irrigation water management. Some of the yields achieved with sprinkler and drip irrigation systems are several times larger than average yields achieved on farms in Syria and in other countries with similar production conditions. Closing the sugar-beet yield gap would probably require substantial investments in new irrigation equipment and large expenditure on supplemental fertilizer that may not be feasible on many farms at this time. However, the results provide motivation for examining current water management and fertilizer strategies in order to identify incremental improvements in cultural practices that would enable farmers to achieve higher yields.

Sawmi *et al.* (2001) compared crop yields and the average productivity of water and fertilizer on cotton plots irrigated with basins, sprinklers and drip systems in Syria. Between 1991 and 1995, the drip-irrigated plots provided the highest average yields and required the lowest average water applications (Table 42). In particular, sprinklers and drip systems reduced water application by 26 and 55 percent, while yields increased by 35 and 42 percent compared with basin-irrigated plots. As a result, the estimated average productivities of water and fertilizer are substantially higher on the sprinkler and drip-irrigated plots.

In 2000, the Surbaya research station in Aleppo Province and the Tezeen research station in Hama Province, Syria, conducted further research into the potential gains from sprinkler and drip irrigation on laser-levelled plots (Sawmi *et al.*, 2001). The highest yields at Surbaya were from plots with sprinklers spaced at 9 m by 9 m, while the drip-irrigated plots received the lowest water application (Table 43). The sprinkler yield was 7 percent higher than the drip-irrigated yield, but the water application on the sprinkler plots was 52 percent higher. As a result, the average water use productivity was higher on the drip-irrigated plots. The estimated fertilizer use productivity was 7 percent higher on the sprinkler plots, as both sets of plots received the same applications of fertilizer. The cotton yield was 6 percent higher and the water application was 3.4 percent less on 100-m furrows than on 140-m furrows at Surbaya. This result is consistent with expectations regarding lower distribution uniformity on fields irrigated with the longer furrows. The results achieved at Tezeen in 2000 are similar to those at Surbaya. Cotton yields were higher and water applications were smaller on plots irrigated with sprinklers and drip systems than on surface-irrigated plots. The drip-irrigated yield was 30 percent larger than the yield obtained using basin irrigation, while the volume of water delivered on the drip-irrigated plots was 60 percent smaller. As a result, the average water use productivity was 3.4 times higher on the drip-irrigated plots, while the estimated fertilizer use productivity was 30 percent higher.

TABLE 43

Water and fertilizer productivity with basin, furrow, sprinkler and drip irrigation, Aleppo and Hama provinces, Syria, 2000

Province and irrigation method	Applied water (m^3/ha)	Crop yield (kg/ha)	Average product of applied water (kg/m^3)	Average product of fertilizer (kg/Syrian pound))
Aleppo (Surbaya)				
Basins	14 168	3 514	0.25	0.87
Furrows (100 m)	11 089	4 215	0.38	1.04
Furrows (140 m)	11 470	3 980	0.35	0.98
Sprinklers (9 m x 9 m)	9 696	4 785	0.49	1.18
Drip irrigation	6 385	4 475	0.70	1.10
Hama (Tezeen)				
Basins	13 244	3 613	0.28	0.89
Furrows (100 m)	9 656	4 115	0.43	1.02
Sprinklers (9 m x 9 m)	6 676	4 586	0.78	1.13
Drip irrigation	4 889	4 685	0.96	1.16

Note: Treatments at Surbaya and Tezeen received 190 kg/ha of N as urea and 62 kg/ha of P_2O_5 as triple superphosphate. US$1 = 123 Syrian pounds in 2001 (EIU, 2001a).

Source: Sawmi *et al*., 2001, as reported in FAO, 2001b.

TABLE 44

Fertilizer and water productivity with different irrigation methods, wheat, Deir Al-Zoor, Syria

Study	Grain yield (kg/ha)	Applied water (m^3/ha)	Applied water use productivity (kg/m^3)	Gross fertilizer use productivity (kg/kg)
Sawmi *et al*. (1997): 1991-96				
Basin irrigation	4,294	8,789	0.47	15.9
Surface irrigation	5,570	6,261	0.89	20.6
Sprinkler irrigation	5,746	4,954	1.16	21.3
Sawmi *et al*. (1998): 1992-97				
Strips at 2 litres/s/m	5,067	7,367	0.69	18.8
Strips at 3 litres/s/m	4,544	8,602	0.53	16.8
Strips at 4 litres/s/m	4,367	9,374	0.46	16.2
Farmer’s irrigation	3,600	9,092	0.36	13.3

Notes: All treatments in both studies received 120 kg/ha of P_2O_5 and 75 kg/ha of N before planting, and 75 kg/ha of N at tillering. Irrigation strip treatments are in terms of litres per second per metre of width.

Source: FAO, 2001b.

Sawmi *et al*. (1997, 1998) examined the impact of irrigation systems on water use and fertilizer productivity on wheat plots at the Mreiya research station in Deir Al-Zoor, Syria, from 1991 to 1997. In one study, sprinklers using smaller water volumes achieved higher grain yields in comparison with surface and basin irrigation methods (Table 44). The average volumes of applied water were 8 789, 6 261 and 4 954 m^3/ha on the basin, surface and sprinkler irrigated plots. As a result, the average productivity of water use was considerably higher on the sprinkler-irrigated plots. In a similar study conducted from 1992 to 1997, the average yield obtained with irrigation strips and a discharge rate of 2 litres/s per metre of width was 5 057 kg/ha, while the average yield obtained with traditional irrigation methods was 3 600 kg/ha. Average grain yields were higher and applied water volumes were smaller at lower discharge rates, within the strip irrigation treatments. As a result, the average water productivities also increased with reductions in the discharge rate.

Sawmi *et al*. (1995b, 1995c) examined the impact of irrigation methods on maize yields and the average productivity of water and fertilizer at the Al-Nashabiya experiment station, Syria,

TABLE 45

Fertilizer and water productivity with different irrigation methods, maize, Al-Nashabiya Station, Syria, 1993-1995

Irrigation treatment	Crop yield (kg/ha)	Evapotranspiration (m^3/ha)	Applied water (m^3/ha)	Average product of water: ET_a (kg/m^3)	Average product of water: Applied (kg/m^3)	Average product of fertilizer (kg/kg)
Sawmi *et al.*, 1995b						
Surge flow (1 litre/s)	7 473	4 034	5 429	1.85	1.38	18.2
Surge flow (2 litres/s)	8 030	4 074	5 105	1.97	1.57	19.6
Sawmi *et al.*, 1995c						
Syphons (2 litres/s)	7 483	3 844	5 595	1.95	1.34	18.2
Surge flow (2 litres/s)	8 060	4 013	4 934	2.01	1.63	19.7
Sprinklers	8 178	4 116	4 680	1.99	1.75	19.9

Notes: The data for all treatments in Sawmi *et al.*, 1995b, describe average values obtained during two seasons: 1993 and 1994. The data for the syphon-tube and sprinkler treatments in Sawmi *et al.*, 1995c, describe average values obtained during three seasons: 1993-95. The data for surge flow irrigation in Sawmi *et al.*, 1995c, describe average values obtained during 1994 and 1995. Irrigations applied when soil moisture reached 75% of field capacity. Plots laser levelled with 70-cm furrow spacing. On all plots, 80 kg/ha P_2O_5 and 70 kg/ha K_2O broadcast and mixed with surface soil before planting. In addition, 80 kg/ha N as urea applied with irrigation water at each of three stages: germination, vegetative growth, and milky stage.

Sources: Sawmi *et al.*, 1995b and 1995c, as reported in FAO, 2001b.

between 1993 and 1995. These authors obtained higher yields than those reported by Sharabi *et al.* (1982) and Khalifa and Mohammed (1991) for two reasons: (i) the soils at Al-Nashabiya are less saline than soils in the lower Euphrates River basin; and (ii) the distribution uniformity of irrigation water is generally higher on laser-levelled plots, resulting in higher crop yields (FAO, 2001b). In particular, Sawmi *et al.* (1995b) obtained average maize yields of 7 473 and 8 030 kg/ha in 1993 and 1994 using surge flow irrigation on laser-levelled plots with a furrow spacing of 70 cm (Table 45).

All plots received supplemental applications of phosphorus and potassium (broadcast and mixed with surface soil before planting) and an application of nitrogen at three stages during the season. The higher yields of maize, combined with irrigation efficiencies of 74 and 80 percent, resulted in average productivities of water use of 1.85 and 1.97 kg/m^3 of evapotranspiration and 1.38 and 1.57 kg/m^3 of applied water. Similar maize yields, irrigation efficiencies and average products of water and fertilizer resulted from using syphon tubes, surge flow irrigation and sprinklers between 1993 and 1995. In particular, average yields ranged from 7 483 to 8 178 kg/ha, while average water applications ranged from 4 680 to 5 595 m^3/ha, resulting in irrigation efficiencies of 69, 81 and 88 percent for syphon tubes, surge flow and sprinklers. Estimated average products were about 2.00 kg/m^3 of evapotranspiration for all systems, while ranging from 1.34 to 1.75 kg/m^3 of applied water. Comparing similar amounts of fertilizer, the estimated average products of fertilizer are also higher than those reported by Sharabi *et al.* (1982) and Khalifa and Mohammed (1991). The results reported by Sawmi *et al.* (1995b, 1995c) reflect total nutrient applications of 390 kg/ha and an average fertilizer use productivity of about 19 kg/kg. By comparison, average productivities ranged from 8.0 to 12.5 kg/kg on treatments receiving 330 kg/ha of nutrients (Table 27) and from 4.5 to 9.5 kg/kg on treatments receiving 410 kg/ha of nutrients (Table 28). Hence, the combination of laser levelling and improvements in irrigation methods on less saline soils appears to generate higher estimated average productivities of both irrigation water and fertilizer.

Sawmi *et al.* (1996) also compared surge flow irrigation, sprinklers and surface irrigation with traditional irrigation methods at the Tezeen research station in Hama, Syria between 1993 and 1996. Maize yields were smaller at the Tezeen station than those reported by Sawmi *et al.* (1995b, 1995c) for the Al-Nashabiya station. The Al-Nashabiya plots received potassium

TABLE 46

Fertilizer and water productivity with different irrigation methods, maize, Tezeen Station, Syria, 1993-96

Irrigation treatment	Crop yield	Evapotrans-piration	Applied water	Average product of water		Average product of fertilizer
				ET_a	Applied	
	(kg/ha)	(m^3/ha)	(m^3/ha)	(kg/m^3)	(kg/m^3)	(kg/kg)
Surge flow (1.25 litres/s)	6 340	4 900	6 896	1.29	0.92	14.9
Surge flow (2.25 litres/s)	6 137	5 949	6 848	1.03	0.90	14.4
Sprinklers	5 583	4 917	6 277	1.13	0.89	13.1
Surface	5 583	4 998	8 044	1.12	0.69	13.1
Farmers' traditional	4 937	5 193	9 065	0.95	0.54	11.6

Notes: Irrigations applied when soil moisture reached 75% of field capacity. All treatments received 125 kg/ha P_2O_5 as triple superphosphate and two applications of nitrogen: (i) 150 kg/ha N as urea broadcast and mixed with the surface soil before planting; and (ii) 150 kg/ha N as urea applied 50 days after planting.

Source: Sawmi *et al.*, 1996, as reported in FAO, 2001b.

TABLE 47

Fertilizer and water productivity with different irrigation methods, maize, Al-Mreiya Station, Syria, 1990-95

Irrigation treatment	Crop yield	Evapotrans-piration	Applied water	Average product of water		Average product of fertilizer
				ET_a	Applied	
	(kg/ha)	(m^3/ha)	(m^3/ha)	(kg/m^3)	(kg/m^3)	(kg/kg)
Farmers' traditional	4 520	5 245	11 154	0.86	0.40	11.3
Surface	4 913	4 897	7 664	1.00	0.64	12.3
Sprinklers	5 008	5 684	6 918	0.88	0.72	12.5

Notes: Irrigations applied when soil moisture reached 75% of field capacity. All treatments received 150 kg/ha P_2O_5 as triple superphosphate and two applications of nitrogen: (i) 125 kg/ha N as urea broadcast and mixed with the surface soil before planting; and (ii) 125 kg/ha N as urea applied 50 days after planting.

Source: Sawmi *et al.*, 1995a, as reported in FAO, 2001b.

fertilizer before planting (FAO, 2001b), but the plots at the Tezeen station did not. The maize yields at Tezeen ranged from 4 937 kg/ha using traditional methods to 6 340 kg/ha on fields irrigated by the surge flow method with a discharge rate of 1.25 litres/s (Table 46). Irrigation efficiencies ranged from 57 percent on the traditional plots to 87 percent on the surge flow (2.25 litres/s) plots, for estimated average products of water ranging from 0.95 to 1.29 kg/m^3 of evapotranspiration and from 0.54 to 0.92 kg/m^3 of applied water. The estimated average products of fertilizer ranged from 11.6 to 14.9 kg/kg, reflecting the lower yields obtained at Tezeen.

Sawmi *et al.* (1995a) reported lower yields and average products of water and fertilizer at the Al-Mreiya station in Deir Al-Zoor, Syria (Table 47), where the soil is slightly saline and received no additional potassium for (FAO, 2001b). The irrigation efficiencies were 47, 64 and 82 percent for the three treatments, resulting in estimated average products of water ranging from 0.86 to 1.00 kg/m^3 of evapotranspiration and from 0.40 to 0.72 kg/m^3 of applied water. Estimated average products of fertilizer range from 11.3 to 12.5 kg/kg.

The results obtained in Syria by Sawmi *et al.* (1995a, 1995b, 1995c and 1996) vary among locations with differences in fertilizer applications, climate and soil conditions. However, at all locations, crop yields, irrigation efficiencies and the estimated average products of water and fertilizer generally increased with improvements in irrigation methods. In general, the average volumes of water applied were much lower when using the improved irrigation methods. The difference is a substantial volume of water in an arid region with very limited water supplies. The difference in irrigation volumes at Al-Mreiya was 4 236 m^3/ha, or more than 60 percent of the water applied using sprinklers. Many issues require examination before recommending a switch from traditional surface irrigation methods to sprinklers and surge flow methods. These issues include investment costs, operation and maintenance costs, and the cost and availability of support services. However, the data generated in the studies reviewed here suggest that the potential gains to improving water management on maize fields in Syria may be substantial.

The extent of water resources available and the high gypsum content of soils in the Euphrates River basin have limited irrigation development in Syria. Hence, rainfed agriculture produces most of the nation's agricultural output. However, many farmers in some areas have installed wells and pumps in order to obtain groundwater for irrigation. In some of these areas, the sum of withdrawals exceeds annual recharge, causing concern regarding the sustainability of irrigated agriculture. Waterlogging and salinity are also a concern in some areas. Efforts to improve productivity in Syria will probably focus on both irrigated and rainfed areas. Research regarding sprinkler and drip irrigation suggests that these methods may enhance crop yields while reducing water withdrawals, but farmers may not be able to afford such systems. Further research regarding water harvesting in rainfed areas and an intensive programme to enhance water and nutrient management in both rainfed and irrigated areas may be helpful in improving agricultural productivity in Syria.

Balanced input applications with a variety of crops

Ahmad (2001) described the results of research conducted by the Pakistan Agricultural Research Council regarding optimal water and fertilizer applications for wheat, maize, cotton and sugar cane. Crop yields obtained in the study are substantially higher than average yields reported in aggregate agricultural statistics. For example, wheat yields ranged from 2 874 to 5 710 kg/ha, with a mean yield of 4 052 kg/ha, while national and provincial average yields of irrigated wheat in Pakistan are generally less than 3 000 kg/ha. Maize yields reported in the study ranged from 2 137 to 4 260 kg/ha, with a mean yield of 2 699 kg/ha, while average yields of maize are generally less than 1 600 kg/ha. Cotton and sugar cane yielded similar results. A comparison of farm-level fertilizer strategies with recommended applications in some of the research described by Ahmad (2001) reveals that the farm-level fertilizer applications were deficient in one or more of nitrogen, phosphate and potassium, while the recommended strategy included a balanced application of all three nutrients. For example, the farm-level fertilizer treatment for wheat included 67, 34 and 34 kg/ha of N, P_2O_5 and K_2O respectively while the recommended treatment included 67, 67 and 34 kg/ha of the nutrients (Table 48). The study also examined the impact of moisture stress on crop yields. The scheduling was for irrigation when moisture stress reached 1, 4 and 7 bars. Combining the two fertilizer treatments with three irrigation strategies resulted in six treatments on plots of wheat, maize and sugar cane at different locations for either two or three years. The average yields obtained with the recommended fertilizer programme were larger than those obtained with the farm-level strategy in all of the irrigation treatments, although the difference in average yields declined with an increase in moisture stress. In particular, the yield difference in wheat declined from 24 percent on plots receiving 4 030 m^3/ha and 3 830 m^3/ha of irrigation water to 17 percent on plots receiving 3 400 m^3/ha of irrigation water. The maize and sugar-cane plots provided similar but more dramatic reductions in yield differences. These results demonstrate that both moisture and fertility management contribute to higher yields and that neither moisture nor fertilizer alone will generate maximum yield. Switching from the farm-level to the recommended fertilizer programme will provide a relatively small increase in yield in conditions of severe moisture stress. Similarly, increasing the volume of irrigation water applied will provide only a moderate increase in yields if the fertilizer programme is deficient in amount or imbalanced.

TABLE 48

Water use productivity with moisture stress and fertilizer treatments, Pakistan

Crop and Moisture	**Water used**	**Yields**		**Water use productivity**			
research station	**stress**	**(ET_a)**	**F1**	**F2**	**F2/F1**	**F1**	**F2**
	treatment	(m^3/ha)	(kg/ha)	(kg/ha)	(ratio)	(kg/m^3)	
Wheat							
Mona reclamation	M1	4 030	4 620	5 710	1.24	1.15	1.42
Project (3 years)	M2	3 830	4 383	5 430	1.24	1.14	1.42
	M3	3 400	4 200	4 927	1.17	1.24	1.45
Maize							
Mona reclamation	M1	4 310	1 873	2 480	1.32	0.43	0.58
Project Bhalwal	M2	3 860	2 020	2 260	1.12	0.52	0.59
(3 years)	M3	3 580	1 780	1 900	1.07	0.50	0.53
Sugar cane							
AARI Faisalabad	M1	13 900	62 742	77 314	1.23	4.51	5.56
(2 years)	M2	11 700	62 329	70 352	1.13	5.33	6.01
	M3	10 500	60 617	60 875	1.00	5.77	5.80

Notes: Moisture stress treatments:

M1: Irrigation at 1 bar tension (13.1% moisture content).
M2: Irrigation at 4 bar tension (8.4% moisture content).
M3: Irrigation at 7 bar tension (7.0% moisture content).

Fertilizer treatment:

		N	P_2O_5	K_2O
Wheat:	F1:	67	34	34
	F2:	67	67	34
Maize:	F1:	56	0	34
	F2:	168	34	34
Sugar cane:	F1:	75	0	0
	F2:	225	112	112

Source: FAO, 2001d.

ELASTICITY STUDIES

Hussain and Young (1987) estimated Cobb-Douglas production functions for local and improved wheat varieties using survey data collected from 140 farms in Punjab, Pakistan. The estimated parameters of a Cobb-Douglas function describe the proportional responsiveness, or elasticity, of a dependent variable with respect to an independent variable. For example, the parameter estimate of 0.374 for irrigation water applied on local wheat varieties (Table 49) suggests that a 10-percent increase in irrigation water may increase yields by 3.74 percent. The estimated parameters are statistically significant for irrigation water, nitrogen fertilizer and seed for both local and improved varieties. The estimated parameter for phosphate is not statistically significant in the production function for improved wheat. This result may reflect the relatively high mean rate of phosphate application reported by farmers in the survey. At 168 kg/ha of phosphate, the incremental yield obtained with additional phosphate application may not be significantly different from zero. The estimated parameters regarding salinity impacts are negative and statistically significant in both production functions. Results suggest that a 10-percent increase in soil salinity may reduce the yields of local and improved wheat varieties by 0.47 and 1.22 percent. One also may infer that a 10-percent reduction in soil salinity might increase wheat yields by a similar proportion. By using the regression results and the farm-level price of wheat, it is possible to generate estimates of the MVPs of irrigation water and fertilizer. A comparison of the estimated MVPs with input prices, or opportunity costs, can help determine whether farmers are choosing profit-maximizing amounts of selected inputs. For example, the estimated MVP of an irrigation event is 79 rupees on local wheat and 55 rupees on improved wheat, while the estimated cost of obtaining canal water is 30 rupees per irrigation event (Table 50). Hence, it appears that the limited volume of water available in the canal system

TABLE 49

Production functions for wheat varieties in Punjab, Pakistan, 1985

	Local wheat		Improved wheat	
Estimated coefficient	**Parameter estimate**	**Standard error**	**Parameter estimate**	**Standard error**
Constant	-0.132	0.064	0.021	0.195
Irrigation water	0.374	0.072	0.532	0.089
Nitrogen fertilizer	0.186	0.084	0.214	0.084
Phosphate fertilizer	0.356	0.050	-0.021	0.083
Water salinity	0.051	0.048	0.045	0.053
Soil salinity	-0.047	0.035	-0.122	0.083
Seed	0.366	0.040	0.197	0.080
Regression R^2	0.93		0.79	

Source: Hussain and Young, 1987.

TABLE 50

Marginal value product and opportunity cost of irrigation water and fertilizer for wheat varieties in Punjab, Pakistan, 1985

Estimated coefficient	Marginal value product	Opportunity cost
Local wheat:	(rupees)	
Irrigation water		
Mean of 5 irrigations per year	79.00	30.00
Nitrogen fertilizer		
Mean of 8.9 kg/ha	27.52	3.25
Phosphate fertilizer		
Mean of 58 kg/ha	55.88	30.45
Improved wheat:		
Irrigation water		
Mean of 6 irrigations per year	55.00	30.00
Nitrogen fertilizer		
Mean of 7.4 kg/ha	43.98	3.25
Phosphate fertilizer		
Mean value of 168 kg/ha	n/s	n/s

Source: Hussain and Young, 1987.

may be a constraint on farm-level water use. Similarly, the estimated MVPs of nitrogen fertilizer greatly exceed the estimated farm-level cost of nitrogen, and the estimated MVP of phosphate on local wheat exceeds the farm-level cost.

Chaudhary *et al.* (1998) estimated four translog profit functions using data from a survey of 484 farms in irrigated areas in Punjab, Pakistan. The estimated functions include one aggregate function for Punjab using all of the data and three functions pertaining to rice, cotton and mixed cropping zones using subsets of the data for those areas. Labour, education, capital and fertilizer are among the explanatory variables in all four functions. Labour and fertilizer are complementary inputs in all of the estimated functions, such that higher levels of fertilizer use correlate with higher levels of farm labour. The estimated price elasticity of demand for fertilizer is -1.46 (Table 51). This may be especially pertinent when considering the potential impact of reductions in fertilizer subsidies. The estimated elasticity of output with respect to fertilizer price is -0.80. Levels of fertilizer use are higher on farms where the farmers have achieved higher levels of education. The estimated elasticities of fertilizer use with respect to education range from 0.21 in the mixed cropping zone to 0.71 in the rice belt.

Farooq *et al.* (2001) estimated a translog profit function using data on 177 households growing basmati rice in Punjab, Pakistan, in 1995-96. The estimated elasticities of rice output with

TABLE 51

Output and demand elasticities for selected inputs with respect to input and output prices, by cropping zone, Punjab, Pakistan

Elasticity	Rice belt	Cotton belt	Mixed cropping	Punjab
Output with respect to the price of output	0.72	1.45	1.56	0.63
Output with respect to the price of fertilizer	-0.80	-0.63	-0.61	-0.53
Labour with respect to the price of fertilizer	-0.64	-0.98	-0.83	-0.31
Fertilizer with respect to the price of fertilizer	-1.46	-1.94	-0.27	-1.30
Fertilizer with respect to the price of output	1.20	1.66	1.38	1.41
Fertilizer with respect to farmer education	0.34	0.71	0.26	0.21

Source: Chaudhary *et al.*, 1998.

respect to paddy price and fertilizer price are 0.27 and -0.12 respectively. The estimated elasticities of fertilizer use with respect to output price and fertilizer price are 1.18 and -0.75 respectively. This suggests that a 10-percent increase in paddy price would motivate farmers to increase fertilizer use by 11.8 percent, while a 10-percent reduction in fertilizer price would generate a 7.5-percent increase in fertilizer use. The estimated elasticities of demand for fertilizer with respect to output price and for rice production with respect to fertilizer price are higher than those obtained for other variable inputs.

OTHER FACTORS

Karrou (1998) examined the impact of row spacing on wheat yields in semi-arid areas of Morocco. The recommended row spacing for drilled seed is generally 25-30 cm, but such a wide spacing may allow excessive evaporation of soil moisture between plant rows early in the season. Grain yields obtained at the Sidi El Aidi experiment station in 1995-96 and 1996-97 were

TABLE 52

Wheat yields and water use efficiency with two row spacings, Sidi El Aidi experiment station, Morocco, 1995-97

Seeding pattern	1995/96 Grain yield (kg/ha)	1995/96 Rainwater use efficiency (kg/mm)	1996/97 Grain yield (kg/ha)	1996/97 Rainwater use efficiency (kg/mm)
12-cm rows				
200 kernels/m^2	4 380	10.4	1 940	5.9
300 kernels/m^2	3 920	9.3	2 460	8.6
400 kernels/m^2	3 720	8.8	2 520	8.9
Mean	4 020	9.5	2 310	7.8
24-cm rows				
200 kernels/m^2	3 640	8.6	1 740	4.6
300 kernels/m^2	3 730	8.8	1 510	4.1
400 kernels/m^2	2 770	6.6	1 600	4.7
Mean	3 380	8.0	1 620	5.5
Least significant differences (5%)				
Seeding rate	323	1.6	NS	NS
Row spacing	274	1.1	382	1.5
Interaction	NS	NS	NS	NS

Notes: Soil moisture not measured in 1995/96. Rainwater use efficiency in 1995/96: grain yield divided by rainwater received. Water use efficiency in 1996/97: grain yield divided by crop evapotranspiration. Seeding dates: 16 November 1995 and 2 December 1996. All treatments received 60 kg/ha N, 60 kg/ha P, and 40 kg/ha K.

Source: Karrou, 1998.

significantly higher on plots with row spacings of 12 cm than on plots with spacings of 24 cm (Table 52). Measurements of water use efficiency were also higher on plots with the closer row spacing. The yields for both row spacings are substantially higher than average wheat yields reported for Morocco in those years, reflecting in part the yield gap that exists between farm-level and experiment station yields.

By constructing microbasins to reduce surface runoff and by weeding them in order to reduce competition for moisture, it may be possible to enhance wheat yields and water use efficiency on sloping lands in the rainfed areas of Morocco. Bouaziz and Chekli (1999) obtained higher grain and straw yields on weeded microbasins in two out of three years in the early 1990s at two locations in Morocco. In particular, the average grain yield on weeded plots without microbasins was 40 percent higher than the average yield on non-weeded plots without microbasins in 1990-91 (Table 53). The average yield obtained on weeded plots with microbasins was 65 percent higher than the yield obtained on non-weeded plots without microbasins. Treatment effects were larger in 1993-94 when the average grain yield obtained with weeded microbasins was almost three times the average yield obtained on non-weeded plots without microbasins. A dry period lasting nearly two months at the beginning of the crop cycle in 1991-92 resulted in very low yields and no significant treatment effects. Increases in the estimated water use efficiency range from 7 to 30 percent in 1990-91 and from 34 to 37 percent in 1993-94 when comparing weeded and microbasin treatments with the non-weeded plots without microbasins. These data also highlight the substantial variability in wheat yields in rainfed regions, even in experimental settings. The average yields on all four treatments did not exceed 240 kg/ha in 1991-92. Although the rainfall amounted to 484 mm in that period, its distribution of rainfall was not favourable for crop production. The annual rainfall was 40 mm greater in 1990-91, but the distribution was favourable and average yields ranged from 1 160 to 1 910 kg/ha. The yield data for 1993-94 are from a different location, where the 473 mm of rainfall received exceeded the annual average precipitation. Average yields ranged from 1 100 to 3 030 kg/ha at that site in 1993-94. The potential gains with weeding and the use of microbasins appear to increase with precipitation. However, farmers must be willing and able to sustain the risk involved when choosing input levels where the amount and timing of seasonal rainfall have significant impacts on yields.

TABLE 53

Impact of microbasins and weeding on wheat yields and water use efficiency, Morocco, 1990-94

	Wheat yield			**Straw yield**		
Treatment	**1990-91**	**1991-92**	**1993-94**	**1990-91**	**1991-92**	**1993-94**
			(kg/ha)			
Weeded basins	1 910	240	3 030	3 660	1 480	6 280
Non-weeded basins	1 390	240	1 890	3 040	1 440	5 740
Weeded, no basins	1 620	220	2 750	3 430	1 210	6 030
Non-weeded, no basins	1 160	240	1 100	2 800	1 130	4 270

	Water use efficiency					
Treatment	**1990-91**	**1991-92**	**1993-94**	**1990-91**	**1991-92**	**1993-94**
		(grain kg/mm)			(straw kg/mm)	
Weeded basins	6.1	0.7	12.3	11.6	4.3	25.5
Non-weeded basins	4.3	0.7	11.3	9.5	4.2	25.4
Weeded, no basins	5.4	0.7	8.4	11.4	3.6	24.9
Non-weeded, no basins	3.7	0.7	5.1	8.9	3.4	18.6

Notes: In 1990-91, rainfall at the experimental site was 523.3 mm. Total rainfall was 483.7 mm in 1991-92, when a long, dry period occurred from mid-December until mid-February. In 1993-94, total rainfall was 473 mm, higher than the average annual rainfall at the site chosen for the experiment in that year. Rainfall distribution favourable throughout most of the growing season 1993-94.

Source: Bouaziz and Chekli, 1999.

Parikh and Shah (1996) examined data from 397 farms in the Peshawar division of NWFP, Pakistan. In general, smaller farms with less land fragmentation and those located closer to village markets achieve higher levels of technical efficiency. In addition, higher levels of technical efficiency correlate with more years of schooling, larger family size and more frequent visits by extension service personnel. Burki and Shah (1998) obtained similar results regarding the impact of education on technical efficiency using data from 387 farms in Punjab Province. In particular, empirical measures of cost efficiency are higher on farms managed by farmers with higher levels of education. Farmers obtaining a secondary education use more fertilizer than do less educated farmers in the Indus River basin and they achieve higher levels of productivity (Butt, 1984). Salam (1981) found that both tractor use and education correlated with higher levels of fertilizer use in a survey of 179 farmers in Pakistan.

Khan *et al*. (1996) interviewed 450 farmers in the Cholistan area of the Bahawalpur Division in southern Punjab. Most of the farmers are "poor, isolated, subsistence-oriented people" who rely on family labour, while purchasing some farm implements, fertilizer and pesticides in local markets. Primary *kharif* crops include cotton and sugar cane, while *rabi* crops include wheat and fodder. Average crop yields in the study area are lower than average yields for the Bahawalpur District because the Cholistani farmers receive less irrigation water and, therefore, use less of other productive inputs. Canal water is available for about ten weeks following the monsoon season and the volume is sufficient to irrigate 20-30 percent of each farmer's land. The average yields reported in the survey were 1 547 kg/ha for wheat, 1 261 kg/ha for cotton and 25 334 kg/ha for sugar cane, while the corresponding figures for the Bahawalpur District were 2 133, 2 122 and 40 872 kg/ha.

Coady (1995) examined fertilizer use and irrigation data collected from 1 351 wheat-growing households in the Indus River basin, Pakistan. More than 88 percent of the farmers reported using fertilizer, while most of the farmers not using fertilizer reported a shortage of money as the primary reason. More than 50 percent of the farmers interviewed listed insufficient irrigation as the primary reason for suboptimal yields, while 7 percent cited lack of fertilizer as the primary reason. Another 24 percent of the farmers cited lack of fertilizer as the secondary reason for suboptimal yields, while 21 percent gave that as the third reason. Fertilizer use correlated positively with tubewell ownership and with the adequacy of irrigation supplies. In particular, households owning a tubewell appear to apply an additional 14.6 kg of fertilizer per hectare of wheat, while fertilizer use by households classified as having inadequate irrigation supplies was lower by 26.4 kg per hectare of wheat. These results suggest that the marginal productivity of fertilizer is greater where households have access to adequate irrigation supplies.

Ali and Byerlee (1999) examined long-term trends in productivity using district-level data from all 16 irrigated districts in Punjab, Pakistan. They divided the data into three periods: green revolution (1966-1974); intensification (1975-1984); and post-green revolution (1985-1994). They also divided the data according to the dominant *kharif* crop, resulting in four groups: wheat-cotton, wheat-rice, wheat-mung bean (or wheat-fallow) and wheat-mixed summer crops (often maize or sugar cane). Average farm size, the proportion of land leased to tenants and the distance from a paved road have decreased since 1966 in all four groups. Literacy has increased in all groups, rising from an average of 18.8 percent for the whole of Punjab in the first time period (1966-1974) to 28.7 percent in the final period (1985-1994).

Chapter 5
Estimation methods in theory and practice

THE IMPORTANCE OF A CONCEPTUAL FRAMEWORK

The literature review in the previous chapter evidences the many differing approaches to data collection and analysis. Describing data observed in various settings within the context of an underlying conceptual framework enhances the empirical analysis of crop production and input use. Such a framework should include crop production functions that describe how crop yields respond to agricultural inputs and to changes in the quality of environmental resources, such as soil salinity and groundwater quality. It should also include an optimization model that describes how farmers choose input levels and how input and output prices and government policies that modify production and marketing opportunities influence such choices. The crop production data observed in farm-level surveys and case studies reflect prevailing prices and the public policies that influence farm-level decisions.

The relationship involving crop yields, inputs and public policies should allow for interseasonal and intraseasonal dynamic interactions and externalities that describe how irrigation and drainage activities on one farm affect production opportunities on others. In most cases detailed data describing interseasonal and intraseasonal input use, yield responses and externality effects are not available. However, the data observed reflect dynamic interactions and externalities and, hence, it is helpful to acknowledge the complete conceptual framework when interpreting information regarding crop yields and input use.

A DYNAMIC MODEL OF CROP PRODUCTION

A plausible crop production function includes both fixed and variable inputs. Fixed inputs are those that remain constant within a relevant planning horizon such as a crop production season, e.g. the amount of land in production and inherent land characteristics such as slope and natural drainage conditions. Irrigation water, fertilizer, labour and pesticides are variable inputs because farmers can vary the amounts applied within a season. The farm-level stocks of durable inputs and human capital may be fixed inputs within a given season but variable inputs where a planning horizon extends to more than one season.

The assessment of long-term changes in the productivity of fixed and variable inputs requires an interseasonal, dynamic model of crop production. The model must allow for changes in soil characteristics, production technology, capital stocks and other variables that influence crop yields. An appropriate model will include variables farmers choose during each production season and variables that evolve over time as a result of farm-level decisions in accordance with physical relationships involving soil and water resources.

Within a given season, farmers choose the amounts of seed, fertilizer, irrigation water, labour and other variable inputs used in production. These variables are the decision or control variables in a dynamic modelling framework. It is possible to determine the farm-level, profit-maximizing values of control variables by solving an appropriately specified optimization problem.

In arid regions, soil salinity and the depth and quality of a shallow aquifer often affect crop yields. Soil salinity and aquifer characteristics are state variables because they represent the environment in which production takes place. The values of state variables change over time as a function of the amount and quality of decision variables applied by farmers and in response to exogenous factors such as rainfall and other weather conditions. An equation of motion can describe the rate of change in a state variable. In such a variable, its current value is a function of its lagged value and the lagged values of other pertinent state and control variables.

Some state variables such as soil salinity and fertility and depth to a water table affect crop yields directly. Other state variables such as groundwater volume and quality and surface water quality affect crop yields indirectly as many farmers and irrigation districts blend water from different sources when generating irrigation water deliveries. Financial and human capital may also be state variables in a crop production model. Financial capital includes both monetary savings and the stock of durable inputs owned by a farmer, such as tractors, tubewells and irrigation systems. Human capital is the knowledge and skills available within a farm household. The farm-level stocks of financial and human capital change over time largely as a result of investments in new units of those resources and because of changes in policy parameters that affect farm-level investment decisions. For example, government subsidies for investments in tubewells in India and Pakistan have motivated farmers to make those investments at a much faster rate than would have occurred without such subsidies (Aklilu and Hussain, 1992). Education policies and the quality of service provided by agricultural extension agents influence the rate at which farmers accumulate human capital. The importance of education and extension programmes has increased with technological advances in agriculture, increased commercialization and efforts to achieve sustainable production (Faruqee and Carey, 1995).

It is possible to describe a plausible crop production function by defining crop yield (y_t) as a function of state variables (s_t), control variables (c_t) and random shocks (e_y):

$$(1) \qquad y_t = y_t(c_t, s_t, e_y)$$

where c_t and s_t are vectors that include several variables, e_y is a random error term and $y_t(c_t, s_t, e_y)$ denotes a functional relationship. In particular, the vectors c_t and s_t are:

$$c_t = \text{[seeds, fertilizer, irrigation water, pesticides, labour, etc.]}$$

$$s_t = [EC_t, DWT_t, GWV_t, GWQ_t, SF_t, FC_t, HC_t]$$

where: EC_t is soil salinity,

DWT_t is depth to a shallow aquifer,

GWV_t is groundwater volume in a shallow aquifer,

GWQ_t is groundwater quality in a shallow aquifer,

SF_t is soil fertility,

FC_t is the stock of financial capital,

HC_t is the stock of human capital.

The equations of motion that describe how the state variables change over time are:

$$EC_t = EC_t(EC_{t-1}, c_{t-1}, s^{EC}_{t-1}, z_{t-1}, e_{EC})$$

$$\mathrm{DWT}_t = \mathrm{DWT}_t(\mathrm{DWT}_{t-1}, \mathrm{c}_{t-1}, \mathrm{s}^{\mathrm{DWT}}_{t-1}, \mathrm{z}_{t-1}, \mathrm{e}_{\mathrm{DWT}})$$

$$\mathrm{GWV}_t = \mathrm{GWV}_t(\mathrm{GWV}_{t-1}, \mathrm{c}_{t-1}, \mathrm{s}^{\mathrm{GWV}}_{t-1}, \mathrm{z}_{t-1}, \mathrm{e}_{\mathrm{GWV}})$$

$$\begin{aligned}
\mathrm{GWQ}_t &= \mathrm{GWQ}_t(\mathrm{GWQ}_{t-1}, \mathrm{c}_{t-1}, \mathrm{s}^{\mathrm{GWQ}}{}_{t-1}, \mathrm{z}_{t-1}, \mathrm{e}_{\mathrm{GWQ}}) \\
\mathrm{SF}_t &= \mathrm{SF}_t(\mathrm{SF}_{t-1}, \mathrm{c}_{t-1}, \mathrm{s}^{\mathrm{SF}}{}_{t-1}, \mathrm{z}_{t-1}, \mathrm{e}_{\mathrm{SF}}) \\
\mathrm{FC}_t &= \mathrm{FC}_t(\mathrm{FC}_{t-1}, \mathrm{NR}_{t-1}, \mathrm{fc}_{t-1}, \mathrm{fcx}_{t-1}, \mathrm{e}_{\mathrm{FC}}) \\
HC_t &= HC_t(HC_{t-1}, NR_{t-1}, fc_{t-1}, hcx_{t-1}, e_{HC})
\end{aligned}$$

where the subscript *(t-1)* denotes the values of variables and vectors in the previous time period and e_j is a random error term in the jth equation of motion, where $j = EC, DWT, GWV, GWQ, SF, FC$ and HC. The vectors denoted as $s^j{}_{t-1}$ include all of the variables in the vector s_{t-1} except the state variable corresponding to the value of j. For example, the vector $s^{EC}{}_{t-1}$ includes all state variables except EC_{t-1} as that value already appears as the first variable in the equation of motion for soil salinity.

Irrigation and drainage activities on neighbouring fields often influence the soil salinity, depth to water table and groundwater quality pertaining to any one field. For example, excessive irrigation by some farmers may cause the water table to rise beneath the field of other farmers, potentially contributing to the waterlogging and salinization of neighbouring fields. The vector z_t in the crop production model represents the set of irrigation and drainage activities on neighbouring fields. In particular, the vector z_t is:

z_t = [irrigation depths, evapotranspiration, deep percolation, surface runoff, and irrigation water quality on neighbouring farms or fields]

Lagged values of the vector z_t appear in the equations of motion for soil salinity and fertility, depth to water table, and groundwater volume and quality.

The equations of motion for financial and human capital include the lagged value of farm-level net revenue (NR_{t-1}) as farmers are more likely to invest in capital during years in which net revenue is positive. The vectors fc_t and hc_t include the choice variables for activities that enhance financial and human capital. Attending school, participating in agricultural training events and reading crop production materials can enhance human capital. Purchasing new equipment, repairing machinery, and upgrading irrigation technology can enhance financial capital. The appropriate equations of motion include lagged values of those choice variables.

The vectors fcx_t and hcx_t include variables representing exogenous factors that influence farm-level decisions on investment in financial and human capital, such as the price and availability of educational services and the number and quality of training sessions available to farmers. Government policies regarding interest rates on savings and loans, the price and availability of credit and taxes or subsidies on specific production technologies can influence farm-level decisions regarding capital investments. The equations of motion for human and financial capital include lagged values of these exogenous variables.

ANALYTICAL IMPLICATIONS

Long-term effects

The dynamic crop production model depicts crop yield as a complex function in which physical, economic and political factors affect the many state and control variables. In particular, the yield of any crop is a function of inputs chosen by farmers in both current and past seasons because previous input choices affect the evolution of state variables that influence crop yields in the current season. Similarly, policy variables that influence farm-level investments in human and financial capital can have lasting impacts on crop yields through interactions involving both state and control variables. Rewriting the crop production function of Equation (1) using lagged values of the state and control vectors can highlight the time dimension of such interactions:

$$(2) \qquad y_t = y_t\,(c_t,\, s_t\,(s_{t-1},\, c_{t-1}\,),\, e_y\,)$$

Recalling the variables included in s_{t-1} and c_{t-1} illustrates one to see how farm-level decisions, the value of state variables, government policies and interactions among neighbouring farmers in one year influence crop yields in a subsequent year. It is possible to extent the recursive nature of this equation in order to depict current crop yield, y_t, as a function of state and control variables in any previous year, such as year *t-2*, *t-3*, etc.

Average and marginal productivity

The production function in Equation (1) or Equation (2) describes total yield, in units per hectare, as a function of state and control variables and a random error term. Economic models of crop production often refer to total yield as total product or total physical product (TPP). The average productivity of a variable input is its average physical product (APP), which is the TPP divided by the amount of a variable input used in production. For example, the average productivity of nitrogen fertilizer is:

$$(3) \qquad \mathrm{APP_N} = y_t\,/c_{1t} = y_t\,(c_t,\, s_t,\, e_y\,)/c_{1t}$$

where c_{1t} is the amount of nitrogen, N, applied to a field in tonnes per hectare and c_{1t} is one element of the control variable vector c_t. The resulting measure of $\mathrm{APP_N}$ is in units of yield per units of nitrogen, such as kilograms of yield per kilogram of nitrogen applied to a field.

$\mathrm{APP_N}$ is also a function of both current and lagged values of state and control variables. Hence, past values of farm-level decisions and policy variables that influence those decisions can affect crop yields and average productivity in future years. This result pertains to the average productivity of any variable input.

A similar logic holds for the incremental productivity of variable inputs, known as the marginal physical product (MPP). The MPP is the partial derivative of TPP with respect to a variable input. For example, the MPP of crop yield with respect to nitrogen fertilizer is:

$$(4) \qquad \mathrm{MPP_N} = \delta y_t/\delta c_{1t} = \delta y_t\,(c_t,\, s_t,\, e_y\,)/\delta c_{1t}$$

Hence, the incremental productivity of nitrogen fertilizer is also a function of current and lagged values of state and control variables and of farm-level interactions and government policies that influence those variables.

Rosenzweig and Iglesias (1994 and 2001) used an MPP approach to develop relationships between crop yield and optimal irrigation water demand for key crops in different agroclimatic regions that represent important areas of global agricultural production. They defined MPP as the change in crop yield to each additional unit of supplemental irrigation water applied. They then used the MPP to evaluate the value of irrigation water for each region, because the product of the MPP and the price of the crop gives an estimation of the value of the irrigation water in each region. This enabled an analysis of 25 countries that represent main areas of world agricultural production and contrasting production systems. Using 138 sites to represent climate and farming conditions around the world, Rosenzweig and Iglesias (1994) specified management conditions for validated crop models for wheat, rice, maize and soybeans. The simulated or estimated crop parameters were:

- Dryland yield (*Yd*): crop yield only rainfed, that is the only water that the crop and soil receive is the rainfall water (different for each site), expressed in kilograms per hectare.
- Irrigated yield (*Yi*): crop yield with irrigation water applied to obtain maximum yield (the total water received by the crop and soil is the rainfall plus the irrigation water), expressed in kilograms per hectare.
- Irrigation water (*I*): the water applied to the crop for obtaining maximum yield, expressed in millimetres per crop season.
- Marginal physical product (MPP): the relationship of the change in crop yield to each additional unit of irrigation water applied, expressed in kilograms per hectare per millimetre. The simulated crop parameters yield the MPP: MPP = $(Yi - Yd)/I$.

However, Rosenzweig and Iglesias (1994, 2001) also point out the limitations of MPP estimates. For example, the crop models make a number of simplifying assumptions: weeds, diseases, and insect pests are under control; there are no problem soil conditions (e.g. salinity or acidity); and there are no extreme weather events. The models are calibrated to experimental fields, where yields are often higher than those under farming conditions. At the regional level, the primary source of uncertainty in the estimates lies in the sparseness of the crop modelling sites to derive regional MPPs and the fact that the sites may not adequately represent the variability of water allocation regions, the variability of agricultural systems within a water region, or dissimilar agricultural regions.

Equations (3) and (4) demonstrate the difficulty of isolating the impacts of any one variable input on crop yield. Both the average and marginal productivity of nitrogen fertilizer are potentially functions of all other control variables and the state variables that influence crop yields. The vectors c_t and s_t appear in the definitions of both average and marginal productivity. Some functional forms for the production function may allow the separation of the effects of one variable input from others, but such forms may not provide an accurate portrayal of agricultural production. In most cases, it is likely that the average and marginal productivity of fertilizer are functions of the amount and quality of irrigation water, pesticides, labour and other inputs applied during the season. In addition, it is reasonable to expect that soil salinity, depth to water table, human and financial capital and other state variables also affect the average and marginal productivity of fertilizer, irrigation water and other variable inputs.

The random error term, e_y, in Equations (1) and (2) also appears in Equations (3) and (4). This term accounts conceptually for pest outbreaks, weather events, poor growing conditions and other factors that may affect crop yields in a random, unexpected manner. The variables included in the production function do not capture these effects. Crop yield data observed on farms and throughout production regions will reflect the impact of random events and the effects of any variables not included explicitly in a production model. Random events contribute to the observed variation in crop yield data and to estimates of average and marginal productivity. Hence, there needs to be some allowance for random events when interpreting farm-level crop production data.

Externalities

Irrigation and drainage activities on adjacent fields and on fields located some distance away can affect crop yields positively or negatively. For example, some farmers in the Nile Delta have difficulty growing cotton near rice-growing areas because the seepage under rice fields causes the water table to rise beneath adjacent fields (Kotb *et al.*, 2000). In many irrigated regions, excessive irrigation by farmers located at the head ends of tertiary canals contributes to waterlogging and salinization of soils near the tail ends of those canals. Such interactions are externalities because the individuals generating the impacts receive no recompense for any positive effects, nor do they pay for any damage caused to other farmers.

Externalities come under the vector z_t that appears in lagged form in each of the state equations involving soil and water resources. Hence, externalities from irrigation and drainage affect both total yield and the average and marginal productivity of variable inputs. In regions where deep percolation beneath some farms contributes to waterlogging or salinization on other farms, the average and marginal productivity of improved seed varieties, fertilizer or irrigation water may be much lower than expected in the absence of externalities. The impact of externalities may increase over time where farmers are unable to leach salts away from the rootzone.

Where negative externalities are present throughout irrigated regions, aggregate crop yields and aggregate measures of average and marginal productivity will be lower than similar statistics for regions without such externalities. For example, the prevalence of waterlogged and saline areas reduces average crop yields on the Indo-Gangetic plains. Groundwater pumping externalities that occur in regions with large numbers of private tubewells also reduce crop yields and productivity. Individual farmers gain the benefit of water they extract using tubewells without paying for the scarcity value or the opportunity cost of limited groundwater supplies or for any incremental effects on regional pumping lifts. As a result, groundwater pumping lifts are increasing in many areas of India and Pakistan at the same time as groundwater quality is declining (Ahmad and Faruqee, 1999).

The impacts of public policies

Economic theory suggests that profit-maximizing farmers will equate the price of a variable input with its MVP when choosing how much of the input to use in production. Intuitively, farmers will use additional units of a variable input as long as the value of incremental production is greater than the incremental cost. In a competitive market, the output decisions of any one farmer do not affect output price and the MVP is the output price multiplied by the MPP of the input. Hence, the profit-maximizing equi-marginal criterion is:

$$(5) \qquad (\text{Price of the input})_t = (\text{Price of the output})_t * (\text{MPP of the input})_t$$

Many of the public policies implemented by regional and national governments have a significant impact on one or more of the terms that appear in Equation (5). For example, many governments support agricultural revenues by establishing floor prices at which a state agency will purchase a given commodity. Governments also extract revenues from agriculture by requiring farmers to sell their output to state-run agencies in return for a fraction of the world market price. Policies that boost farm-level prices will encourage greater use of variable inputs, while policies that reduce farm-level prices will cause reductions in input levels. Farmers may also shift input use from one crop to another in response to a government policy that modifies farm-level crop prices. For example, many farmers in Egypt diverted fertilizer and other inputs from cotton to other crops in the 1980s owing to heavy implicit taxation of cotton by the government (Richards, 1991). As a result, both the area planted to cotton and the average productivity of land declined.

Many state and local governments modify input prices using direct or indirect policy tools. For example, the public electricity utilities in India and Pakistan charge farmers a price that depends on the size of the motor used to operate an electric tubewell or on the size of area irrigated, rather than the time for which the motor is in operation (Faruqee, 1996; Shah *et al.*, 2000). Such flat-rate pricing encourages farmers to use excessive amounts of electricity and groundwater. An alternative pricing scheme in which monthly water costs increase with pumping hours or with the volume of water extracted would encourage efficient use. Electricity subsidies contributed substantially to the rate of increase in crop yields following the green revolution by providing farmers with an affordable and reliable water source. However, current extraction rates in many areas are not sustainable (Kijne, 2001a). Subsidies on fertilizer have also contributed to the yield gains achieved in recent decades, but the cost to national treasuries has often been substantial. Many governments have been reducing fertilizer subsidies in recent years.

Governments affect the MPP of inputs indirectly through investments in research, training and extension programmes. Scientific discoveries at national and international agricultural research centres often generate new crop varieties or improvements in crop production technologies that enhance the MPPs of selected variable inputs, either alone or in combination with other inputs. The modern varieties of wheat and rice introduced during the green revolution increased the marginal productivities of irrigation water and nitrogen fertilizer substantially. Training and extension programmes generally enhance the human capital of participating farmers, enabling them to maximize the potential gains from new varieties and other modern inputs.

Public policies also affect farm-level incentives regarding investments in financial and human capital both directly and indirectly. Policies regarding input and output prices affect farm-level expectations regarding potential net returns from alternative enterprises. These expectations in part determine whether farmers invest in new machinery and seek training programmes to enhance their knowledge and skills. Policies regarding interest rates, exchange rates, tariffs and quotas affect farm-level crop prices and the prices and availability of internationally traded inputs.

Policies intended to accomplish one goal may often complicate efforts to achieve other goals or increase pressure on natural resources unexpectedly. For example, subsidies on electricity prices and investments in tubewells on the Indo-Gangetic plains contributed to remarkable gains in aggregate food crop production during the 1970s and 1980s. However, in areas with saline groundwater, the subsidies have contributed to increasing the rate of soil salinization. In areas with good quality groundwater, the subsidies have contributed to unsustainable rates of groundwater overdraft. In the Nile Delta, policies that restrict farm-level prices and marketing options for cotton encourage farmers to grow rice, leading to increased demand for irrigation water and placing greater stress on the water delivery system.

The equi-marginal criterion in Equation (5) involves only current prices of inputs and outputs and the current MPP of inputs. However, policy measures that affect current input and output prices can have long-term impacts on resources and on farm-level decisions, given the role of state variables described by the dynamic model of crop production. For example, policies that motivate farmers to use more saline groundwater in a current season may contribute to higher soil salinities in future seasons. Policies that encourage farmers to replace cotton with rice may contribute to waterlogging and salinization problems that persist for many years. In addition, policies that modify farm-level incentives regarding investments in financial and human capital can have long-lasting impacts on the marginal productivity of both fixed and variable inputs.

EMPIRICAL IMPLICATIONS

Estimating the average or marginal productivity of agricultural inputs at any point in time is a challenging task given the existence of externalities and the impacts of dynamic interactions and public policies on farm-level decisions and the evolution of state variables. The average and marginal productivities of inputs change over time with changes in the underlying production functions. These changes may be gradual and monotonic where technological progress is steady, there are no resource constraints, negative externalities are not substantial, and policy parameters are relatively stable. However, in many agricultural settings, the increasing demand for limited land and water resources generates negative externalities that can cause rapid contractions in production functions. At the same time, structural adjustment programmes can require governments to reduce or remove interventions in input and output markets, causing farmers to reconsider their production and marketing choices at short notice. For example, the sharp reductions in fertilizer use that often follow the withdrawal of fertilizer subsidies can cause a rapid reduction in the marginal productivities of land and irrigation water. Estimates of marginal productivities made before the adjustment programme may no longer be valid.

Several sources of information are available for use in describing the average and marginal productivity of variable inputs in agriculture. These include studies conducted at experiment stations, on-farm trials supervised by researchers and extension specialists, farm-level data reported in surveys and case studies, district-level and county-level data compiled from information provided by farmers and regional and national crop report statistics. It is possible to describe variations in the quality, accuracy and reliability of analytical results obtained using data from different sources within the context of the dynamic crop production model. In particular, data obtained from different sources will reflect different components of the dynamic model. Acknowledging these differences can enhance the value of the results obtained and sharpen the policy recommendations generated by empirical research.

Data from experiment stations often describe the crop yields obtained in highly controlled, closely managed production settings where all inputs except those under study remain at optimal or prescribed levels. For example, studies of yield response to nitrogen fertilizer often involve varying the amount of nitrogen applied, while holding other nutrients constant at prescribed levels. Hence, the data generated by experiment station studies generally represent a stylized production setting that does not usually reflect actual growing conditions in farm fields.

Most experiment station studies do not reflect the impact of externalities or public policies on crop yields, either in one season or over time. Long-term studies can reflect some of the dynamic interactions described above. However, such studies often take place in non-typical production settings, where the human capital input exceeds that of most farming operations, financial capital is not limiting and it is possible to manage physical capital more effectively over time. For example, soil salinity may be less of a problem on long-term plots found on an experiment station than on farms in regions where externalities contribute to waterlogging and salinization.

One goal of conducting on-farm trials is to enhance the applicability of experimental results by generating data in actual farm settings. Studies often compare crop yields on farmer-managed plots with crop yields on plots managed by researchers. The quality of information generated in on-farm trials varies with the level of effort invested in simulating true farm-level conditions on the experimental plots. It also depends on the degree of researcher input into management decisions on both the farmer-managed and researcher-managed plots. It is reasonable to expect that crop yields obtained on both types of plots will be lower than those obtained on experiment stations owing to externalities and dynamic interactions that influence farm production settings.

Farm-level data obtained in surveys should reflect all the externalities, dynamic interactions and policy effects described above. Hence, the data should provide an accurate view of total, average and marginal productivity in an agricultural area. However, given the complex interactions that generate farm-level data in non-controlled environments, researchers may not be able to identify and describe the average or marginal productivity of a single input with desirable accuracy. In addition, it is necessary to recognize issues regarding measurement error and data quality when working with farm-level information. Many researchers have used statistical and regression techniques to analyse such data. However, summary statistics describing the accuracy of parameter estimates are often less impressive than desired owing to considerable variation in the data collected in farm-level surveys. The main causes of such variation are the heterogeneity of soils, drainage conditions, management inputs, and the levels of financial and human capital.

County-level and district-level crop production data often make use of information provided by farmers regarding total farm-level output and the total amounts of selected inputs used in crop production. Many irrigation districts in the western United States of America compile annual crop reports that depict the total production and the area of land harvested for each major crop and the total volume of water delivered to each farmer. These data are helpful in understanding aggregate production values and trends, but they are less helpful in describing actual crop yields or the productivity of variable inputs. County-level crop reports often make use of the information collected by irrigation districts and other local agencies. Hence, these reports are also of limited value when examining trends in the productivity of selected inputs.

Regional and national crop production statistics often make use of county or province-level reports. Hence, these statistics also are helpful in describing long-term trends in aggregate production, but are of limited value when seeking detailed information regarding changes in the productivity of selected inputs. Dividing aggregate crop production values by the number of hectares planted or harvested in a region or nation can provide an average production value per hectare. However, the numerical result is not truly an average crop yield and it does not contain information describing the degree of variation in crop yields by year, by region or across farms within a given region. The same holds for calculations involving aggregate crop production values and aggregate amounts of a variable input used in production. For example, dividing the total amount of wheat produced in a region or nation by the total amount of nitrogen fertilizer applied on land planted to wheat gives the average amount of wheat produced per tonne of nitrogen. However, this numerical result provides an aggregate overview of wheat production and fertilizer use, but it does not describe directly the farm-level average productivity of nitrogen fertilizer.

In summary, there is not one single, optimal source of information for use in examining the average and marginal productivity of agricultural inputs. Researchers need to work with a mixture of data from different sources that range from experiment station studies to aggregate national statistics. The availability and quality of data varies by country and by agricultural activity. For example, many recent studies have examined the decline in growth rates of rice and wheat yields on the Indo-Gangetic plains. These studies provide a large amount of data from experiment stations, farm-level surveys and case studies conducted by national and international research centres. In addition, FAO compiles aggregate data describing crop production and input use for many countries, including those that span the Indo-Gangetic plains. It is often necessary to analyse data from several sources in order to determine the causes of declining rates of growth in crop yields and to develop policy alternatives that may be help restore productivity growth.

INTRASEASONAL DYNAMICS

The interseasonal model of crop production described above includes a single time subscript denoting a specific production season or year. Hence, variable inputs include the amounts of seeds, fertilizer, irrigation water and pesticides applied throughout a season. In practice, farmers apply many of these inputs more than once during a season and the timing of applications may have a significant impact on crop yields. For example, the timing of fertilizer applications relative to soil moisture conditions and plant nutrient requirements can influence crop yields substantially. The same is true for the timing of irrigation water deliveries relative to crop water requirements and rainfall events.

The timing of inputs that are applied only once per season can also influence crop yields. For example, the sowing time can have a significant impact on yields, particularly in arid regions where crops require rainfall in order to germinate or become established. The delayed planting of wheat after cotton has probably contributed to the declining growth rates in wheat yields on the Indo-Gangetic plains in recent years. Experimental data suggest that wheat yields in Punjab, Pakistan, may decline by 30 kg/ha for each day that farmers delay planting beyond mid-November (Byerlee *et al*., 1987). In upper Sindh, Pakistan, a one-week delay in planting may reduce wheat yields by 97 kg/ha (Flinn and Khokhar, 1989). Cotton yields in Syria may decline by 7 percent where the delay in planting is 15 days and by 20 percent where the delay is 30 days (FAO, 2001b). Priming seed by soaking it overnight in a 0.2-percent gypsum solution to reduce germination time increased wheat yields by an average 36 percent on 20 farm trials in NWFP, Pakistan (Harris *et al*., 2001).

In the absence of intraseasonal data, empirical estimates of average and marginal productivity may be less accurate than desired. For example, the marginal productivity of wheat seed applied just before a germinating rain may be higher than the marginal productivity of seed applied two weeks later. In some cases, farmers will replant a field if a severe rain or wind event destroys a substantial portion of seedlings shortly after the initial planting. In such cases, the average productivity of seed will appear much lower than if a single seeding event had been sufficient. Researchers examining seasonal seed use data may be unaware of the replanting that occurred during the season. Similarly, the marginal productivity of fertilizer applied when soil is moist may be greater than the marginal productivity when the soil is dry, but researchers may lack information describing intraseasonal applications and soil moisture conditions.

Data describing the intraseasonal timing of input applications are rarely available from any sources other than experiment stations. Some farm-level surveys and case studies include intraseasonal information. However, few studies collect detailed data at the times that input applications actually take place. Most studies report data collected at the end of a season by asking farmers to recall the timing of input applications. Although these studies do provide some insight regarding intraseasonal interactions, the proper analysis and interpretation of the intraseasonal information often requires more detailed information regarding soil moisture conditions, nutrient status and weather events. Such detailed, intraseasonal data may be available only in experiment station studies.

Given the difficulty of obtaining useful intraseasonal data, this report does not address this issue further. However, it is important to acknowledge that even very detailed data describing seasonal inputs and outputs may not describe fully the average or marginal productivity of key inputs where the timing of application is an important consideration.

A conceptual framework that describes the near-term and long-term interactions among inputs and measures of land and water productivity may enhance the interpretation of empirical information describing crop yields, input use and changes in productivity. Such a framework should include crop production functions in which irrigation water, fertilizer, labour, machinery and drainage systems are key inputs. The framework should also allow for consideration of land and water quality impacts on crop yields both in the near term and over time.

PRACTICAL PROBLEMS AND SHORTCOMINGS OF THE STUDY

The approach to a conceptual framework outlined above may appear attractive. However, as this report illustrates, there are many practical problems relating to data collection, information requirements, the role of new technology, and compilation methods.

Initially, in addition to examining water and fertilizer use in terms of factors affecting their use and their productivity in different settings, this study set out to: (i) examine the effect of output in relation to resource use; and (ii) compare and contrast basin irrigation with poor water control, surface irrigation in gravity schemes with potential sound water control systems, and tubewell irrigation with closed water supply.

However, although it may be logical to assume that farmers will adopt a rational, profit-maximizing approach to input use, it is difficult to make firm conclusions based on reported data in situations where they operate under non-market conditions. In the three sample countries, the impacts of subsidies, support prices and other forms of government intervention make it difficult to determine meaningful marginal product values. Moreover, it would be unsound to extrapolate the data that are available to other countries and to free-market situations.

Furthermore, although this report reviews a considerable number of studies, comparisons are not easy. Researchers use different experiment procedures and evaluate their results using different methods. Thus, experiment data on water and fertilizer use on a given crop in one site in one country are not directly comparable with data from another country. There are differences in terms of physical conditions, cultivar types, amount and frequency of water and fertilizer applications, etc. This situation calls for a more comprehensive and uniform approach where the aim is to make recommendations on input use that are valid not just at one experimental site but for an area, region, country or indeed at the global level. However, this does not presuppose a one-size-fits-all approach to research.

The study's original intention to compare irrigation systems at various levels clashed with the reality of a paucity of reliable, comparable data. Such comparisons require detailed data. The gathering of such data often calls for the use of sophisticated technologies. While such technologies may be readily available in developed countries, in some developing countries the related costs currently limit their use. These costs relate not only to the initial purchase but also to operation, maintenance and training.

Chapter 6
Conclusions

This report has highlighted the role of irrigation and fertilizer use in enhancing food security, improving rural incomes and supporting economic development.

The information from experiment stations and survey data illustrates the potential gains from improving farm-level physical and economic conditions, e.g. applying fertilizer and irrigation water at appropriate times and at optimal rates can boost crop yields significantly. Hence, it is important to improve farm-level access to fertilizer and water and to provide farmers with better information on optimal soil and water management practices.

GENERAL CONCLUSIONS

Much of the research and many of the field observations described in this report suggest viable paths to restoring productivity growth, especially in the sample countries. The challenge is to develop and implement policy reforms that will encourage farmers to use limited resources efficiently without causing substantial disruption to current levels of economic activity and employment.

Public programmes that enhance farm-level educational opportunities and provide credit at affordable rates may help restore soil productivity in affected areas and motivate farmers to adopt input levels that are consistent with long-term sustainability goals. Similar education and credit programmes can encourage improved use of irrigation water from both surface and groundwater sources, so reducing the rate of increase in waterlogged and salinized areas.

In rainfed areas, programmes might focus on promoting investments in water harvesting skills and equipment and on reducing the risk of applying fertilizer. Small increases in the use of supplemental irrigation water and fertilizer in rainfed areas can generate substantial gains in productivity. However, risk-averse farmers are reluctant to use expensive inputs in regions where a severe water shortage at a critical stage of crop development can reduce crop yields sharply. A public programme that transfers some of the risk associated with irrigation investments and fertilizer use in rainfed areas may be appropriate given the public benefits generated by improving aggregate food production and enhancing employment opportunities.

Improvements in agricultural technology such as genetic modification of plants and better methods for reducing crop losses to insects and pathogens could contribute significantly to achieving required gains in aggregate output. In addition, improvements in the transportation and storage of agricultural products in developing nations will generate important gains in net production. However, it will remain necessary to make substantial improvements in the quality of soil and water resources that support agricultural production.

There should be a greater focus on policies and programmes that allow input and output prices to reflect true market values and opportunity costs. New measures should include proactive elements to enhance the financial and human capital components of farm operations. The opportunities for improving input productivity are real and the optimal farm-level responses to them will enhance the prospects of achieving and maintaining food security throughout the developing world.

IRRIGATION AND FERTILIZER USE

Although important singly as productivity enhancing inputs, this report demonstrates that it is in combination that water and fertilizer are most effective at boosting crop yields. Much of the research described in this report demonstrates the complementarity of fertilizer and irrigation water in both irrigated and rainfed conditions. In many studies, small applications of fertilizer and irrigation water have improved yields substantially. From the analysis of the experiment and survey data, it also is possible to make the following conclusions:

- The estimated average products of water and fertilizer increase with the volume of irrigation water applied, and the proportional gains in yield can exceed the proportional increases in applied water and the amount of fertilizer.
- While irrigation and fertilizer inputs can generate substantial increases in crop yields, above certain levels the law of diminishing marginal returns applies to input use.
- Yield response to fertilizer varies with moisture conditions and sowing date.
- The water use efficiency of supplemental irrigation increases with increasing nitrogen.
- Fertilizer use may tend to increase with the average number of irrigations.
- Both moisture and fertility management contribute to higher yields but neither moisture nor fertilizer alone will generate maximum yield.

IRRIGATION

This study has documented how the average productivity of land and water resources in the three sample countries varies with the degree of irrigation development. In particular, it has shown that average yields of major crops are significantly higher in irrigated areas than in rainfed zones. Furthermore, the incremental values of inputs such as fertilizer and the seeds of HYVs are generally higher in irrigated areas than in rainfed zones. In addition, analysis of the experiment and survey data suggests the following conclusions concerning the productivity of water use in agriculture:

- Both cropping intensity and irrigation intensity have increased.
- Profit-maximizing farmers who receive a partial irrigation supply that is insufficient to maximize yield on all of their land will apply irrigation water to maximize the net return per unit of water received.
- It is important to select an appropriate goal with respect to supplemental irrigation and crop yields, particularly in regions with limited water supplies.
- The availability of irrigation water enhances the high-yielding variety (MVP) of land in agriculture.
- Many farmers cite insufficient irrigation as the primary reason for suboptimal yields, and the limited volumes of water available in canal systems may be a constraint on farm-level water use.
- Careful irrigation water management can improve wheat yields substantially above those on rainfed fields.

- Overall yields tend to increase with an increased frequency of irrigation events, and the timing of such events can be an important factor in enhancing water use productivity. However, average water use efficiency first rises but then declines as irrigation frequency increases. Hence, it is important to determine the economically optimal number of irrigations by comparing the value of incremental yield obtained with an additional irrigation event with the incremental cost of irrigation.
- The average productivity of water use (and of fertilizer use) is often considerably higher on drip, strip and sprinkler-irrigated plots.
- Before recommending a switch from traditional surface irrigation methods to sprinklers and surge flow methods, it is necessary to address issues such as investment costs, operation and maintenance costs, and the cost and availability of support services.
- Laser levelling of agricultural fields combined with improved irrigation methods can enhance crop yields and the productivity of water and fertilizer by improving the uniformity of water deliveries where farmers use surface irrigation methods.
- Implementing water conservation strategies could improve the productivity of irrigation water in the near term and reduce pressure from shallow, saline water tables in the long term.
- Staggering the planting of fields may enhance the water use efficiency achieved with supplemental irrigation.
- Incremental returns to irrigation are higher in drier years.
- Row spacing can have a significant effect on water use efficiency and hence on yields.
- Land preparation costs tend to rise with the number of irrigations, suggesting that farmers with more frequent and reliable water deliveries are willing to invest more funds in advance of each season.
- Farmers who receive less irrigation water may tend to use less of other productive inputs.

FERTILIZER USE

Much of the data reviewed in this report highlights how fertilizer use generates substantially higher crop yields. In addition, this study comes to the following conclusions:

- Although higher fertilizer application rates generate higher yields, the marginal productivity of fertilizer use diminishes with increases in the amounts applied above a certain level to the point where it would not be economically rational to apply more.
- Banding nitrogen rather than broadcasting the fertilizer may increase yield.
- Applying fertilizer in non-irrigated areas where rainfall is minimal and variable involves a degree of risk that many farmers are reluctant or unable to accept.
- Adding boron and manganese in the fertilizer programme can enhance sugar-beet yields significantly.
- Many farmers cite lack of fertilizer as a reason for suboptimal yields, and many cite lack of money as the reason for not using fertilizer.
- Fertilizer use correlates positively with tubewell ownership and with the adequacy of irrigation supplies, and the marginal productivity of fertilizer is higher where households have access

to adequate irrigation supplies. Fertilizer use also correlates with tubewell installation, as a reliable source of water enhances the productivity of land and fertilizer.

- The reduction in or withdrawal of fertilizer subsidies can result in nutrient deficiencies becoming more extensive.
- Farmers respond to fertilizer prices and output prices when making decisions regarding fertilizer use, and farm-level credit constraints limit the use of fertilizer in some areas.

OTHER PRODUCTIVITY FACTORS

In recent years, the rate of growth in aggregate inputs has tended to exceed the rate of growth in crop production in various regions and crops. The declining rates of growth in both average productivity and cultivated area contribute to the declining rate of growth in total food grain production. Such declining growth rates are in part the consequence of the degradation of land and water resources caused by the inappropriate management of resources on farms and throughout irrigated areas. In part, the public policies that successfully promoted farm-level adoption of green revolution technologies have also contributed to the degradation of soil and water resources.

This report has identified a large number of factors that affect the level and productivity of water and fertilizer use. Some relate more to water use, e.g. waterlogging, salinization, degradation, water table rise, drainage, seepage, and irrigation system design and maintenance. Others relate more to fertilizer use, e.g. nutrient imbalance, while others affect both water and fertilizer use, e.g. resource availability and management, crop rotations, soil fertility, research (and its dissemination), mechanization, weeds, disease, the use of HYVs, and the level of risk at farm level. In addition, some factors affect water and fertilizer use at the macro level: the role of government (policy, subsidies, support prices, crop procurement programmes, tariffs and trade restrictions); the role of the private sector; and inequities and misallocations that occur in market and non-market economies. These factors are relevant both in the production context and to sustainability and ecological issues. Repairing the damage caused by waterlogging, salinization and poor management of soil fertility will be expensive and time consuming. Changes in public policies could help restore productivity.

Policies that boost farm-level output prices will encourage greater use of variable inputs, while policies that reduce them will cause reductions in input levels. Farmers may also transfer input use from one crop to another in response to a government policy that modifies farm-level output prices. Both economic theory and observations regarding farm-level input use suggest that farmers will not account sufficiently for the long-term impacts of their decisions on soil and water resources where the prices of important inputs do not reflect the related long-term costs. Many authorities modify input prices with undesirable consequences, e.g. flat-rate pricing encourages farmers to use excessive amounts of electricity and groundwater. Pricing schemes should encourage more efficient use. Similarly, fertilizer subsidies have encouraged farmers to increase the intensity of agricultural production, but the relative amounts of nutrients applied each year may not be consistent with maintaining soil fertility.

Government policies that modify the farm-level returns from crop production have also influenced input choices and the evolution of cropping patterns in Pakistan, Syria and Morocco. Implicit taxation of some crops, subsidies for producing others, and mandatory procurement schemes have had significant impacts on farm-level decisions. Government supply of key inputs such as fertilizer, electricity and credit influences the degree to which farmers can obtain and apply them in a timely fashion. For example, any restrictions or delays regarding the availability of seeds and fertilizer can reduce crop yields substantially. Persistent difficulties in obtaining inputs may cause farmers to modify cropping patterns to include less profitable or less appropriate crops.

Public policies also affect farm-level incentives regarding investments in financial and human capital both directly and indirectly. Policies regarding input and output prices affect farm-level expectations regarding potential net returns from alternative enterprises. These expectations in part determine whether farmers invest in new machinery and seek training programmes to enhance their knowledge and skills. Policies regarding interest rates, exchange rates, tariffs and quotas affect farm-level crop prices and the prices and availability of internationally traded inputs. Governments can affect the productivity of inputs through investments in research, training and extension programmes. However, policies intended to accomplish one goal may complicate efforts to achieve other goals or increase pressure on natural resources unexpectedly.

Labour and fertilizer are complementary inputs, such that higher levels of fertilizer use correlate with higher levels of farm labour. This may be significant for rural employment prospects.

Smaller farms with less land fragmentation and those located closer to village markets achieve higher levels of technical efficiency. In addition, higher levels of technical efficiency correlate with more years of schooling, larger family size and more frequent visits by extension service personnel. Levels of fertilizer use and productivity are higher on farms where the farmers have a higher level of education. In addition, empirical measures of cost efficiency are higher on farms managed by farmers with higher levels of education. Moreover, education and tractor use correlate with higher levels of fertilizer use.

Describing data observed in various settings within the context of an underlying conceptual framework can enhance the empirical analysis of crop production and input use. Such a framework should include crop production functions (describing yield response to inputs and changes in the quality of environmental resources) and an optimization model that describes how farmers choose input levels and how input and output prices and government policies influence such choices. The crop production data observed in farm-level surveys and case studies reflect prevailing prices and the public policies that influence farm-level decisions. The relationship involving crop yields, inputs and public policies should allow for interseasonal and intraseasonal dynamic interactions and externalities. However, pertinent, reliable data are often unavailable and this currently restricts efforts to validate theoretical models, especially in developing countries that lack the resources to invest in new data-collection technologies.

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