AN ECONOMETRIC STUDY OF THE ECONOMIC VALUE OF IRRIGATION WATER IN THAI AGRICULTURE

By

VARAPORN PUNYAWADEE

A Thesis Submitted to the Faculty of Graduate Studies
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for the Degree of

DOCTOR OF PHILOSOPHY

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Abstract

This study estimates shadow prices of irrigation water to farmers in Thai agriculture using both cross section farm level data and time series national data. Static primal (production function) models are specified and estimated using farm level and national level data, and static dual models (of output supply and input demand) are specified and estimated with the national level data.

Empirical results from the farm level analysis are based on survey data on agricultural production in crop year 1991/92 in the Huai Mae On irrigation project area, located in Sankampang district in the province of Chiang Mai. The estimated marginal value of irrigation in rice production in the 1991 wet season is 673 baht per rai (or approximately 230 Cdn.$ per hectare). Of the major five crops (garlic, shallot, groundnuts, soybeans, and cucumbers) produced in the 1992 dry season, the estimated marginal value of irrigation is highest in garlic production (2,010 baht per rai or 684 Cdn.$ per hectare) and lowest in soybeans production (195 baht per rai or 66 Cdn.$ per hectare).

Empirical results from the national level analysis (based on time series data from 1969 to 1990 for the wet season and 1975 to 1990 for the dry season) vary substantially across alternative models. Point estimates of the marginal value of irrigation water in rice production vary from 1,457 to 7,519 and 487 to 1,148 baht per rai (or from 495 to 2,560 and 165 to 390 Cdn.$ per hectare) in wet season and dry season, respectively.

Although econometric analysis is limited to static models, this study also extends the theory of shadow prices for resource stocks in dynamic models. This is achieved by extending recent analyses of dynamic envelope theorems. A comparison of formulas for shadow prices in static and dynamic models suggests conditions under which static models may provide a reasonable approximation to shadow prices in dynamic models.

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I wish to express my gratitude to my major advisor, Dr. Barry T. Coyle for his generous encouragement throughout the course of my study. His valuable advice and extraordinary help from the conceptualization of this thesis to putting it into the final form has been profoundly appreciated. I am also grateful to Dr. John A. Gray and Dr. Gary V. Johnson for participating on my advisory committee. Their critical suggestions and comments have been extremely useful to the improvement of this thesis. Special appreciation is also due to Dr. Terrence S. Veeman for his role as the External Examiner.

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Chapter 1. Introduction

1.1 Background of the Study

1.1.1 A Brief Overview of the Current State of Water Resources in Thailand

Water, once perceived as an abundant renewable resource in many countries, is rapidly becoming a scarce resource due to pressures from increasing development and population. In Thailand, excessive use of groundwater for domestic and industrial uses has made Bangkok one of the fastest sinking cities in the world. Subsidence rates for land exceed 10 centimetres per year in the areas with extensive groundwater use (Phantumvanit, 1987). Groundwater quality in the Bangkok Metropolitan area has been further degraded by salinity and lack of proper waste disposal. Surface water is also increasingly polluted due to disposal of domestic and industrial wastes into rivers.

In the countryside of Thailand, water resources have continuously been diverted from crop irrigation to supply industries and urban centres and to produce more hydroelectric power. With the industrial sector presently booming, agriculture's share of water has declined significantly. In fact, irrigation water shortages are common especially in the dry growing season.

While conflicts among competing uses for water are growing, rapid urbanization, higher incomes and tourist development also indirectly raise the demand for water over the long run through increased demand for environmental amenities. As income continues to grow and the environment of the cities deteriorates, demand for national parks and golf courses is likely to increase. These trends can be attributed in large part to recent economic growth and industrialization.

1.1.2 Significance of Agricultural Water Use

Thailand has experienced dramatic structural changes during the past 30 years, moving from a subsistence agrarian economy to a rapidly industrializing country. The share of agriculture in GDP has declined from approximately 40% in 1961 to 13% in 1991. Agriculture is projected to account for only 8% of GDP by the year 2000. In contrast, the share for manufacturing and industry has jumped from about 19% of GDP in 1961 to 39% in 1991 and is expected to reach 40% by the year 2000 (Office of the National Economic and Social Development Board; Panayotou et al., 1991).

Nevertheless agriculture remains the major use of water: 90% of fresh water consumption is attributed to agriculture, while 6% and 4% is attributed to industrial and domestic sectors, respectively. The decline in the importance of agriculture might suggest that the demand for water in agriculture will decline, which may tend to offset the rising demand for water outside of agriculture. However, this may not be the case (Sethaputra et al., 1990). Since expansion of the agricultural land base is increasingly difficult, further expansion of agriculture must depend on more intensive use of land. In turn this would lead to an increased reliance on irrigation. Moreover, farmers have no incentive to conserve water since it has been typically provided free of charge.

Since agriculture will remain the major use of water in the foreseeable future, a closer examination of problems in agricultural water use and of mechanisms for improving irrigation water management is apparently critical. More efficient water management is necessary to help curb the water crisis and to help increase the agricultural sector's productivity.

1.2 Problem Statement

Irrigation water management in Thailand has focused on expanding the supply of water rather than on mechanisms for efficient allocation of water. Since irrigation appears to be critical to increases in agricultural productivity, the government has tended to respond to agricultural water shortages by expanding irrigation facilities. The amount of land irrigated has increased almost threefold during the past 30 years, expanding from 9,536,440 rai[1] in 1961 to 27,182,473 rai in 1991. By 1992 the irrigated area accounted for approximately 20 percent of the total agricultural land.

Government research and expenditures on irrigation has been limited to construction of irrigation facilities, especially development of the main systems. Little attention has been given to other factors such as water allocation, users' organization, legal and institutional framework for water use. As a result, irrigation efficiency of on-farm water use may on average be as low as 30% (World Bank, 1985, and Sethaputra et al., 1990).[2] This is mainly attributed to surface losses due to inadequate water management and distribution, runoff, seepage and deep percolation at the farm level. Deterioration of irrigation facilities (dams and canal) due to inadequate attention and maintenance by users has also been apparent.

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[1] 1 rai = 0.16 hectare = 0.396 acre.

[2] Irrigation efficiency (Ei) can be defined as:

$$Ei = \frac{Et-R}{Wg} * 100$$

where Et represents the total amount of water required for crop growth, R denotes the amount of effective rainfall, and Wg is total irrigation water application. Basically, irrigation efficiency consists of two major components: conveyance or distributional efficiency and on-farm water application efficiency.

Demand management[3] to increase efficient use of water has not yet been seriously practised in Thailand despite the growth in demand in recent years and the apparent wasteful use of water. Quantity control has not generally been exercised as an instrument in allocating irrigation water to maximize the benefits. Only during periods of drought have authorities requested cooperation from farmers to reduce the cultivated area in the dry season or to grow crops that require less water.

Prices have seldom been imposed to allocate water among different sectors. Prices charged for residential, state enterprise, and industrial uses have been low due to the low cost of raw water supplies. Irrigation water has generally been provided free of charge. A partial exception is in Northern Thailand where farmers are required to contribute to the administrative costs of water users' organizations but there are no direct charges for water use. If the marginal factor cost of water to farm users is zero, then rational farmers would try to employ water at a level where the marginal value product of irrigation water equals or approaches zero. This equilibrium does not reflect the social opportunity cost of water.

The existing inefficient use of irrigation water, the rapidly growing demand for other competing uses plus the fact that expansion of any new large-scale water resource development project is moving up on a rising supply curve have indicated the need for improved irrigation water performance. Demand management is apparently perceived as most desirable in making more effective use of scarce water.

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[3] Demand management involves measures employed to allocate water within the sector and also among competing sectors (e.g., agricultural, industrial, and domestic uses) to limit waste and induce efficient use and conservation. This issue will be addressed in greater details in Chapter 2.

Since past policies have been oriented toward expansion of irrigated areas justified on the basis of social and political goals, economic assessments of the actual impact of irrigation on agricultural production have not generally been available. Research on the economic value of irrigation water and alternative uses is necessary for establishing pricing policies, use regulations, and also investment criteria. Nevertheless this research has not been conducted.

1.3 Objectives of the Study

The primary objective of this study is to estimate by econometric methods the private economic value (shadow price) of irrigation water using both national level and farm level data. The secondary objective of this study is to estimate the impacts of irrigation on supply of crop outputs and also demand for labour and fertilizer. Due to data limitations it is necessary to employ static methods of analysis, and data on water use is not directly available. Thus a third objective of this study is to compare static and dynamic methods for calculating the marginal value of irrigation water and irrigated land in order to relate the restrictive measures of marginal value constructed here to more general measures. Specifically, this study will address the following objectives:

(i) to construct and compare measures of the shadow price of irrigation water and irrigated land in theoretical static and dynamic models of the firm with irrigation.

(ii) to estimate by econometric methods and compare the private values of irrigation water in Thai agriculture using static economic models with both farm and national level data.

(iii) to estimate by econometric methods the impact of irrigation on crop output supply and variable input demand.

1.4 Scope and Research Methodology

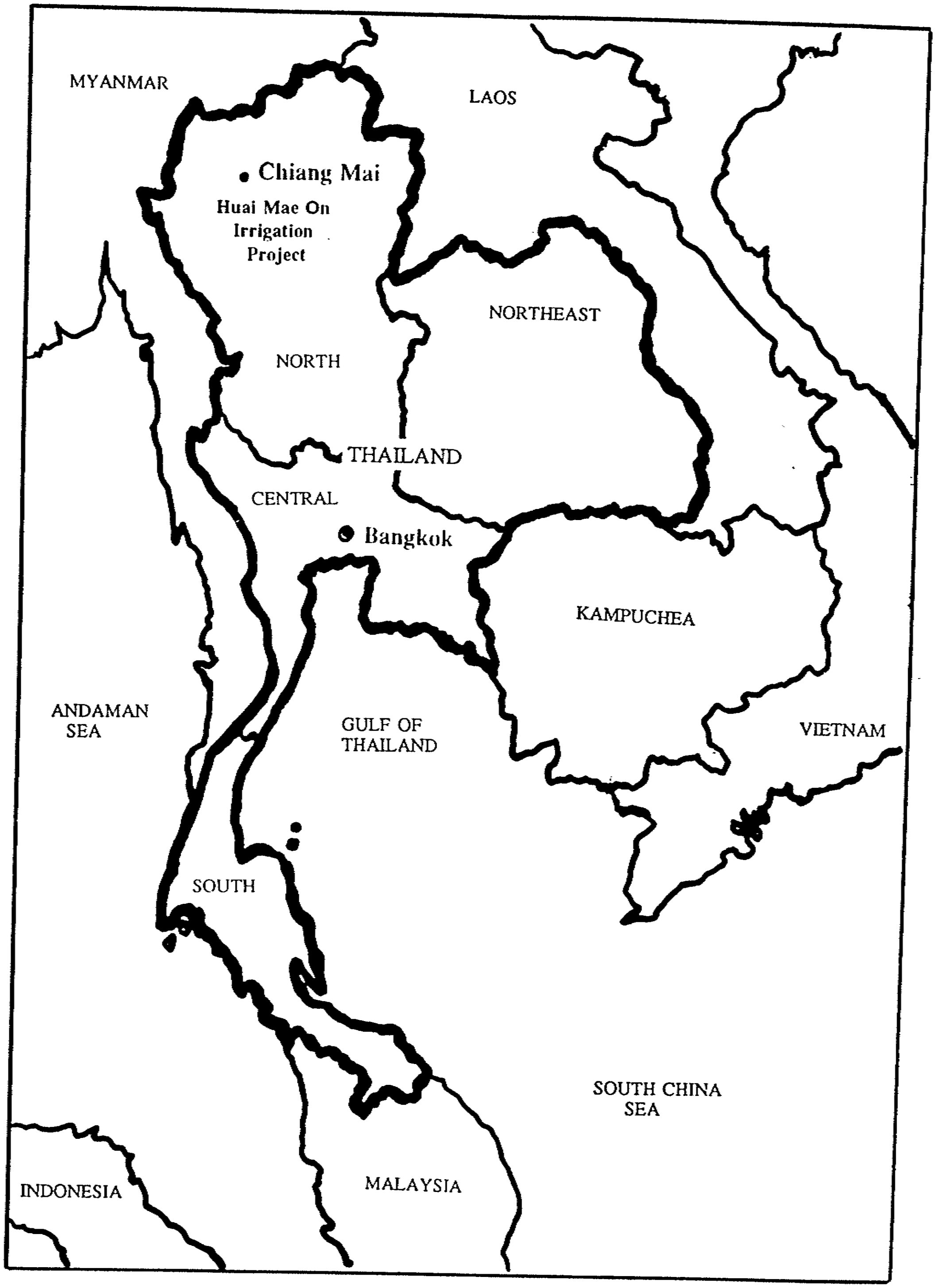
This study primarily attempts to estimate irrigation water productivity or a private shadow price of irrigation water by using both a farm level and a national level data set. The farm (micro) level analysis is conducted using data for farms in a particular irrigation project. Thus the results of this study are conditional on the particular environmental and management conditions at this site. The Huai Mae On (HMO) irrigation project, located in Sankampang district, Chiang Mai province in Northern Thailand is studied here. A map of Thailand with the study location is shown in Fig. 1.1.

Since response to irrigation presumably varies with the level of rainfall and its seasonal distribution, the econometric analysis is attempted for both wet and dry seasons. Cross section survey data employed in the farm level analysis were collected for the 1991 wet season and 1992 dry season from 103 farmers using irrigation water from the HMO project. The survey was assisted by Sankampang deputy-district and subdistrict agricultural officers, a former graduate student from Maejo University and several undergraduate students from Chiang Mai University.

Although there are obvious advantages to analyzing farm level rather than national level data, it is difficult to generalize from a single irrigation project to the nation. For this reason national data was also analyzed in spite of the inevitable errors in aggregation and inconsistencies with such data. Secondary time series data from the crop year 1969/70 to 1990/91 are generally employed in the national level analysis.

Static models are estimated assuming both primal and dual specifications. Primal (production function) models are specified and estimated using farm level and national

Figure 1.1 Map of Thailand and the Research Location



level data. Since there is little price variation in the cross section farm level data set, dual models (of output supply and factor demand) are specified and estimated only with the national level data. The econometric analysis is employed using SAS (version 6.07) and SHAZAM (version 6.2).

Since there are various distortions related to the Thai agricultural sector, the private value of irrigation water (to farmers) is not generally equal to the social value of irrigation water (to society). Nevertheless it is essential to calculate farmers willingness to pay for irrigation because any market-related irrigation policy will not be adopted by farmers unless it is profitable to them. Private values of irrigation water can be interpreted as farmers' willingness to pay for irrigation. Issues crucial to appropriate pricing policy for irrigation water also include methods of charging farmers and controlling water use, but these and other matters are beyond the scope of this study.

Concerning the other objectives of the study, calculation of impacts of irrigation on crop output supply and specified inputs is relatively simple once the econometric models have been estimated. The theoretical analysis of shadow prices in dynamic models and their relation to statics is conducted within the framework of dynamic envelope theorems. Several of these dynamic envelope theorems are original to this study.

1.5 Outline of the Study

This study comprises nine chapters. Chapter 2 provides an overview of irrigation development and irrigated agriculture in Thailand. Policies relating to irrigation water development and management are emphasized. Chapter 3 discusses the theoretical static models which will be employed to estimate the economic water value and to evaluate the impacts of irrigation in the empirical investigations. Chapter 4 compares shadow prices to the firm for irrigation water and irrigation land in theoretical static and dynamic models. Chapters 5 and 6 present and discuss various empirical models that will be used in investigating the productivity of irrigation water and evaluating the impacts of irrigation in Thai agriculture. The empirical results and their qualifications for farm level and national level analyses are then discussed in Chapters 7 and 8, respectively. The thesis then concludes with Chapter 9. This chapter provides a summary of the study, major research findings, and their implications for policy. Recommendations for future research are also noted.

Chapter 2. Irrigated Agriculture in Thailand

2.1 Introduction

This chapter discusses irrigation water resource development and irrigated agriculture in Thailand. The chapter begins with an overview of the agricultural sector. Mention is made of a basic but very critical transformation Thailand is experiencing, a transformation from an agricultural economy to a newly industrialized country. Despite its relative decline in terms of GDP, agriculture remains the dominant sector. An overview of Thai irrigation development and the current state of the regional Thai irrigation network is presented. This is followed by a discussion of crop diversification. Basic data on agricultural land use are provided. Irrigation water management policy is discussed at some length since this may be the key factor affecting irrigation performance.

2.2 The Agricultural Sector

Thailand is situated in Southeast Asia, with a total area of approximately 321 million rai. The country experiences a tropical humid climate.[1] The average annual rainfall is approximately 1,550 millimetres, varying from an average of 1,300 millimetres in the North to an average of 2,400 millimetres in the South. Ninety percent of total rainfall occurs between May and October. The substantial amount of rainfall due to the monsoons, together with an excellent river network, favourable temperature and topography, and fertile soils have made most parts of Thailand highly suitable for

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[1] Three major seasons in most regions of Thailand include the cool season from November through February (when the temperature ranges from 15 to 25 degrees celsius), the hot season from March to May (28 to 38 degrees celsius) and the rainy season from May to October. In the southern part of Thailand, the rainy season normally lasts through December.

commercial rice cultivation.

Historically, agriculture has played an extremely important role in all regions. When the First five-year National Economic and Social Development Plan was initiated in 1961, the agricultural sector absorbed over 85 percent of the total labour force and contributed about 40 percent of gross domestic product (GDP) (Table 2.1).

Table 2.1 Shares of GDP and Employment by Sector

Unit: Percent

Year	GDP/ Employment	Agriculture	Industry	Services
1961	GDP	39.19	19.32	41.49
	Employment	87.4	n.a.	n.a.
1971	GDP	23.90	27.04	49.06
	Employment	79.17	5.33	15.50
1981	GDP	21.36	30.10	48.54
	Employment	71.96	9.63	18.41
1991	GDP	12.64	38.58	48.78
	Employment	62.96	13.97	23.07

Source: National Economic and Social Development Board (NESDB)

Rice production has traditionally formed the core of the Thai economy. Nearly 90 percent of total agricultural land was devoted to rice production in the wet season. Rice is still grown by almost every farmer if soil quality and climatic conditions permit. Rice has not only been the staple grain of the nation, but also the most valuable agricultural export commodity. Rice has typically been the country's largest single source of foreign exchange since the early 1900s. After World War II and prior to 1970, rice contributed about 15-20 percent of total export earnings. Agricultural diversification began in the 1970s, leading to a decline in the relative contributions of rice to 10 percent of export earnings in the 1980s. Nevertheless the absolute volume of rice exports has continued to increase. High quality and low production costs have enabled Thailand to preserve its comparative advantage in the world rice market.

Over thirty years have passed since the inception of the First five-year Plan in 1961. Today Thailand is no longer an agricultural country with a few major agricultural export commodities. Due to the rapid structural change and industrial growth, Thailand is apparently becoming a newly industrialized country (NIC). However, industrialization and economic growth do not always indicate a sustainable growth process. In the case of Thailand, even though the agricultural sector's share in the GDP has dropped to only 13 percent in 1991, the agricultural sector still employs more than 60 percent of the total labour force (Table 2.1). These figures suggest unbalanced growth and inequality of income distribution. As a result, the decline in agriculture's share of GDP does not necessarily imply that agricultural growth is no longer essential to the overall development process. In fact, with the majority of the population still engaged in agriculture even though the sector is shrinking, agricultural growth apparently deserves more attention if a healthier economy is to be attained.

2.3 Irrigation Development

2.3.1 Historical Development of the Irrigation Network

In agricultural production processes, water is obviously an essential input. Even though Thailand receives considerable annual rainfall for agricultural purposes, the uncertainty and uneven distribution of rainfall among regions and over time has often resulted not only in water shortages but also flooding. It has been estimated that farmers whose crops rely only on natural rainfall achieve reasonable output in 3 out of 5 years, but in the other 2 years substantial losses result from delayed and inadequate rainfall or (less frequently) flood damage (Cowley, 1982). Unstable water conditions in agricultural production may provide a rationale for irrigation.

Irrigation, as defined by Clark (1970), is an application of water by a human agency to assist crop growth. In this respect, Thai farmers have been practising simple irrigation for centuries, long before any of the government's direct involvement in the sector. The existence of simple irrigation systems in Thailand can be traced back to as early as A.D. 657 (Surarerks, 1986).

Direct government involvement in irrigation probably began in 1902 when the Canal Department was established to develop and maintain inland waterways, control floods, and build and operate minor irrigation works. However, during that very early development period, irrigation was still not capable of controlling water. The system only consisted of a number of small canals constructed mainly for transportation. These canals were also used to drain water for wet season rice cultivation when the annual flooding occurred.

The successive droughts of 1911 and 1912, led to the development of modern irrigation projects. The main objective (and perhaps the only objective) was to increase rice production in order to meet the needs of a growing population and an expanding rice export market. The first large-scale irrigation project,[2] the Rama VI Dam on the Pa Sak River, was completed in 1924.

In 1927 the Canal Department was reorganized and renamed as the Royal Irrigation Department (RID) with more authority in irrigation development. From the early 1930s to the 1960s the RID focused its efforts on extensive investment in large-scale irrigation systems[3] mainly to assist wet season rice production. More than twenty irrigation projects were constructed during the period of the Great Depression and World War II. As before, almost all of the traditional irrigation technology was designed for extensive wet season rice production.[4] Cultivation in the dry season was not substantially enhanced until completion of two large multipurpose storage dams, i.e., the Bhumiphol and the Sirikit Dams in 1964 and 1972, respectively.

2.3.2 Present Irrigated Area and Prospect for Expansion

RID data[5] indicates that the total irrigated area in Thailand increased by almost 6 percent

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[2] In Thailand, irrigation projects are normally classified into large-, medium-, and small-scale projects. Large-scale irrigation projects are those with capital construction cost over 20 million baht, and these usually have service areas exceeding 80,000 rai. Medium-scale projects are those with construction cost ranging from 4 to 20 million baht or service areas between 6,250 to 80,000 rai. Small-scale projects usually cost less than 4 million baht and have service areas less than 6,250 rai. (1 Canadian dollar=18.37 baht (October, 1994)).

[3] Gravity-flow irrigation systems predominate in the Thai irrigation network. Conceptually, water supplies from upstream to downstream levels are controlled by water regulating structures and gates. Water is delivered through the main irrigation canals which are successively branched into smaller and smaller channels until it reaches farm turnouts (gates at the farmer's field). The excess water at the field is then drained through the channels and is either returned to the system or led away to prevent flooding in the lower areas.

[4] Flooding irrigation method is normally practiced for paddy rice cultivation. The traditional system was specifically designed to spread supplementary water into the rice growing areas as much as possible and only provide the drainage shortly before rice harvesting season begins.

[5] There have been considerable inconsistencies of data available from various sources regarding irrigated areas.

per annum during the 1960s and by approximately 4 percent in the 1970s and early1980s. The rate of increase in irrigated area dropped to 1.6 percent during the second half of the 1980s (Table 2.2).

Table 2.2 Agricultural Irrigated and Rainfed Areas

unit: 1000 rai

Year	Agricultural Land	Irrigated Area	Rainfed Area
1960	61,682.8	9,536.4	52,146.4
1965	78,817.0	10,977.0	67,840.0
1970	92,833.1	12,511.5	80,321.6
1975	112,211.3	15,005.7	97,205.6
1980	118,998.9	18,690.4	100,308.5
1985	128,603.5	23,889.2	104,714.3
1986	129,845.0	24,447.1	105,397.9
1987	131,202.6	24,975.7	106,226.9
1988	131,772.8	25,755.5	106,017.3
1989	131,831.2	25,989.0	105,842.2
1990	132,124.4	26,487.9	105,636.5
1991	133,076.2	27,182.5	105,893.7

Source: *Agricultural Staistics of Thailand*, Ministry of Agriculture and Cooperatives (MOAC), and Irrigated Agricultural Branch, RID.

Currently, the Thai irrigation network consists of approximately 600 large- and medium-scale projects operated under RID supervision, and more than 4,000 small-scale projects operated by farmers. It should be noted that the irrigation systems developed thus far have been based almost entirely on the use of surface water rather than groundwater.

At present, Thailand has approximately 27.2 million rai of irrigated land, accounting for about 20 percent of total agricultural land. It should also be noted that these figures are generally based on the maximum designed irrigation service area when the systems were constructed and this generally overestimates the area actually irrigated. The actual irrigated area in the wet season normally varies from 60-70 percent of the total irrigated land, and only about 25 percent of the total irrigated area has sufficient water for dry season cultivation (Table 2.3).

Table 2.3 Shares of Wet and Dry Season Irrigated Areas Actually Benefitting from Irrigation, 1984-91

Year	Irrigated Area (1000 rai)			Shares (%)	
	Total	Wet Season	Dry Season	Wet Season	Dry Season
1984	22,866.12	16,067.59	5,687.62	70.27	24.87
1985	23,889.15	16,660.78	5,546.21	69.74	23.22
1986	24,447.08	16,854.94	5,986.44	68.94	24.49
1987	24,975.73	17,029.31	6,263.05	68.18	25.08
1988	25,755.53	16,863.02	6,263.05	65.47	24.32
1989	25,989.01	17,580.31	7,092.60	67.65	27.29
1990	26,487.93	16,567.43	7,459.71	62.55	28.16
1991	27,182.47	16,849.95	5,659.36	61.99	20.82
Average	25,199.13	16,809.17	6,244.76	66.85	24.78

Source: Irrigated Agriculture Branch, RID

Even though the fraction of land that is irrigated appears to be relatively low, further expansion of irrigation in Thailand would incur high construction costs (Table 2.4) and apparently also high environmental costs. The principal factor that may have accounted for the dramatic increase in construction cost is that the most suitable sites for constructing dams and their networks were the first to be selected for irrigation. New projects on less suitable sites involve longer canals and more extensive drainage systems.

Table 2.4 Average Investment Cost of Large- and Medium-Scale Irrigation Projects in Thailand (at 1986 Prices)

Year	Numbers of Projects	Investment Cost (million baht)	Service Area (rai)	Average Cost (baht/rai)
1956-65	127	8,356	8,150,025	1,025
1966-75	103	11,552	3,579,670	3,227
1976-86	252	33,803	6,213,932	5,440
Total	482	53,711	17,943,627	2,993

Source: Ammar Siamwalla and Viroj Na-Ranong, 1990.

With respect to environmental consequences, the conservation movement in Thailand has played an increasing role in decisions regarding public irrigation. The most recent plan to construct a large-scale multipurpose dam (the Nam Choan Dam), proposed by the Electric Generating Authority of Thailand (EGAT) in 1980, has received considerable public attention. Even though the government authority has attempted several times to illustrate that the benefits from the project would outweigh the costs, the project has been strongly and severely opposed by local people, environmentalists, and several other interest groups. As written by Suraphol Sudara, one of the leading environmentalists in Thailand,

> It is often said that we do not appreciate the value of things until they are lost. But regret will not do us any good because it will be too late...every dam that we have built resulted in complete destruction of forests... [Thai people] have allowed our resources to be destroyed until the present generation...has to cope with hardship and poverty resulting from degraded natural resources. Only then do we realize that a virgin ecosystem must retain its integrity (Sudara, 1987; p 36).

Due to serious confrontations between conservationists and developers, no large-scale water resource development projects have been implemented in recent years. The outlook for further large-scale irrigation development seems to be rather limited.

2.3.3 Regional Distribution of Irrigation

Table 2.5 shows the distributions of agricultural land and irrigated land among the country's four regions, i.e., the North, the Northeast, the Central, and the South (Fig. 1.1). As clearly indicated, irrigation has been concentrated in the North and Central regions. These two regions account for approximately 75 percent of the total irrigated area in the kingdom.

As shown in Table 2.5, the share of agricultural land in the Northern region is about one fifth of the total. The region is relatively well-equipped with irrigation services, with about one fourth of its total agricultural area irrigated. The Northeast accounts for two fifths of total agricultural land in Thailand, but only 7 percent of agricultural land in the Northeast is irrigated. Water resource conditions in the Northeast are the poorest in the country. The higher lands often suffer from drought while the lowlands along the rivers generally flood. Poor moisture holding capacity resulting from low quality soil texture, in combination with irregular rainfall, apparently contribute to the low level of irrigation development in this region. The Northeast has only 16 percent of the total irrigated land in Thailand.

Table 2.5 Agricultural and Accumulated Irrigated Areas by Region, 1991

Region	Agricultural Area (1000 rai)	Regional Share of Agricultural Area (%)	Irrigated Land (1000 rai)	Regional Share of Irrigated Area (%)	Irrigated land as % of Ag. Land
North	29,394.3	22.09	7,083.2	26.06	24.10
Northeast	57,718.5	43.37	4,371.1	16.08	7.57
Central	28,629.5	21.51	13,013.7	47.87	45.46
South	17,333.9	13.03	2,714.5	9.99	15.66
Whole region	133,076.2	100	27,182.5	100	20.43

Source: *Agricultural Statistics of Thailand*, MOAC.

In contrast, the Central region is the most prosperous region of Thailand. Most land in this region are flood plains or lowlands which are ideally suited for commercial rice production. The region enjoys the most extensive development of irrigation and drainage systems with 45 percent of its agricultural land under irrigation. Almost 50 percent of the country's irrigated land is in this region.

The Southern region is a peninsula. The region experiences a tropical climate which provides adequate moisture and humidity throughout the year. Unlike other parts of the country, the South usually receives more than average rainfall which frequently results in flooding. Approximately 15 percent of agricultural land in this region is irrigated.

It should be emphasized that both the availability of water supplies and land quality have been largely responsible for the geographical distribution of Thai irrigation projects. One important implication for subsequent production analysis is that the differences in productivity between irrigated and non-irrigated land, holding other inputs constant, may be attributable to not only the contribution of irrigation water but also to differences in land quality.

2.4 Cropping Pattern and Diversification

Prior to analyzing the contribution of irrigation water in agricultural production, it is instructive to review cropping patterns during recent years.

2.4.1 Expansion and Diversification on Total Cultivated Land

After the post World War II period, there has been substantial increase in agricultural land area. Agricultural land increased in area by 5 percent in the 1950s, 45 percent in the 1960s, and by 25 percent in the 1970s and the 1980s. As a result, forest lands have been significantly reduced from 54 percent of total land area in 1950 to only 27 percent in 1990.

In addition to rice, the planted area of other major crops has increased substantially. Maize, cassava, sugarcane, soybeans, and mungbeans played important roles in this expansion, with total area planted to these crops increasing tenfold from 1950 to 1990. While the share of total agricultural land planted to rice declined from 67 percent in 1950 to 51 percent in 1990; the share of vegetable and upland crops rose from only 9 percent to 25 percent during the same period. The area planted to these crops increased by over 600 percent during this period (Table 2.6). This process of diversification[6] occurred in response to more diversified market demand and to government policy favouring agricultural diversification in order to counter unstable agricultural prices in world markets.

2.4.2 Diversification on Irrigated Land

Our brief review of the macro picture of cropping patterns illustrates two facts. First, there has been substantial growth in cultivated area during the post World War II period. Most of the post World War II agricultural growth can be attributed to increases in agricultural land area rather than increases in yields. Second, there has been substantial diversification of crops. In addition to rice, several upland crops have played an increasingly important role in expansion of the agricultural sector. However, crop diversification in Thailand has occurred primarily in rainfed areas. A relatively limited amount of diversification has been experienced on irrigated lands (Tables 2.7 and 2.8).

As shown in Table 2.7, rice is still the principal crop on irrigated land especially in the wet season. During the 8 years from 1984 to 1991, approximately 14 to 15 million rai of irrigated land was still planted to rice annually. Although the planted area had not significantly changed in absolute terms, the share of rice on irrigated land had slightly declined from 90 percent in 1984 to 85 percent in 1991. Only 10 to 15 percent of irrigated area had been diversified to other crops such as fruits, vegetable and other upland crops in the wet season.

[6] Due to a lack of data, the discussion here could not be supplemented by comparisons of cropping patterns in the wet and dry seasons.

Table 2.6 Agricultural Land Uses, 1950-90

unit: 1000 rai

Year	Rice	Upland Crops and Vegetable	Fruits and Trees	Wood Land Left Idle	Unclassified Land	Total Agricultural Land	Rice Area as % of Total Ag. Land	Areas of Upland Crops & Vegetable as % of Total Ag. Land
1950	37,374.5	5,038.96	5,769.36	5,365.5	2,148.12	55,696.59	67.10	9.05
1955	36,881.4	4,745.20	5,238.24	5,301.3	4,028.47	56,194.77	65.63	8.44
1960	37,127.1	6,905.63	6,144.93	5,335.8	5,169.34	60,682.83	61.18	11.38
1965	40,493.3	13,495.25	10,432.2	4,962.1	9,434.07	78,817.09	51.38	17.12
1970	59,171.1	13,977.64	9,430.29	4,559.5	5,694.49	92,833.11	63.74	15.06
1975	71,239.2	20,310.71	10,412.5	5,039.5	2,372.13	109,374.16	65.13	18.57
1980	73,562.9	26,072.23	11,142.3	3,064.4	2,636.00	116,478.10	63.16	22.38
1985	73,902.4	32,078.41	13,463.5	3,749.7	2,378.17	125,572.29	58.85	25.55
1990	74,191.4	36,561.93	19,534.8	7,684.3	6,484.76	144,457.26	51.36	25.31

Source: *Agricultural Statistics of Thailand*, MOAC.

Table 2.7 Irrigated Land Uses in the Wet Season, 1984-91

unit: 1000 rai

Year	Rice	Upland Crops	Vegetable	Sugarcane	Fruits	Trees	Fish Farm	Total
1984	14,478.99	173.74	84.14	494.93	392.67	253.19	189.93	16,067.59
1985	14,886.95	169.58	141.76	411.28	585.17	253.44	212.60	16,660.78
1986	14,918.85	115.99	152.81	469.91	618.46	339.00	239.92	16,854.94
1987	15,107.06	129.92	146.15	490.94	579.52	297.78	277.94	17,029.31
1988	14,691.36	131.86	160.36	728.96	570.18	252.62	327.69	16,863.02
1989	15,550.18	131.25	128.52	646.33	644.83	231.37	247.84	17,580.31
1990	14,427.70	110.41	121.94	685.70	715.19	187.18	319.31	16,567.43
1991	14,371.52	138.12	116.87	838.11	789.76	294.12	301.46	16,849.95
Average	14,804.08	137.61	131.57	595.77	611.97	263.59	264.58	16,809.16
%	88.1	0.8	0.8	3.5	3.6	1.6	1.6	100.0

Source: Irrigated Agriculture Branch, RID

Table 2.8 Irrigated Land Uses in the Dry Season, 1984-91

unit: 1000 rai

Year	Rice	Upland Crops	Vegetable	Sugarcane	Fruits	Trees	Fish Farm	Total
1984	3,794.41	785.59	160.22	335.80	348.46	158.29	104.86	5687.62
1985	3,557.34	671.30	171.53	309.23	505.56	148.79	182.21	5546.21
1986	3,476.76	707.70	209.03	383.08	644.62	343.15	222.10	5986.44
1987	3,182.23	700.80	186.54	624.77	647.42	321.55	263.48	6263.05
1988	3,518.49	700.80	186.54	624.77	647.42	321.55	263.48	6263.05
1989	4,373.28	706.41	65.66	680.01	619.10	268.12	268.03	7092.60
1990	4,591.15	710.60	187.31	669.98	805.35	194.46	300.92	7459.71
1991	3,074.52	678.81	182.03	676.50	717.09	128.51	201.92	5659.36
Average	3696.02	707.75	168.61	538.02	616.88	235.55	225.88	6188.71
%	59.7	11.4	2.7	8.7	10.0	3.8	3.7	100.0

Source: Irrigated Agriculture Branch, RID.

Diversification on irrigated land in the wet season has been relatively limited partly because most irrigation systems were designed to serve only extensive rice production (as noted earlier). These irrigation systems generally did not provide the ability to control water at the field level which is required by other crops. Rice is produced best under constant flooding. In contrast upland crops require considerably less water, but they do require much better water control and drainage. This is beyond the capability of the existing irrigation system (World Bank, 1985). The potential for wet season crop diversification on irrigated land is likely to remain low unless the irrigation system is modified to provide a higher degree of water control and better drainage.

The main objective of the government in its irrigation program has been to ensure the rice crop in the wet season which is the principal source of farm incomes. Irrigation for dry season cropping appears to be of secondary importance. Planting area has varied with the water supply remaining in storage reservoirs at the beginning of the dry season. In periods of low rainfall, cultivated area in the dry season can be dramatically reduced if these water supplies are low.

Although paddy rice is the dominant crop under irrigation in the dry season, its share is much lower than in the wet season (Table 2.8). Annual rice area is about 3 to 4 million rai, accounting for about 60 percent of the total irrigated land in the dry season. The remaining 40 percent of irrigated land in the dry season is under other crops. According to the World Bank (1985), farmers continue growing rice in the dry season primarily because the economic return is higher than for alternative upland crops such as soybeans, groundnuts, and mungbeans. Even though rice requires more water than do other crops, it tends to be more profitable in spite of low market prices for rice.[7] This is in part because farmers are not charged for irrigation water.

In addition, physical conditions have also constrained dry season crop diversification on irrigated land. As the World Bank points out,

> ...in terms of soil and drainage only some 15 percent of Thailand's irrigated soils are well suited for upland crops (a further 16 percent has limited potential) and that in fact most irrigation project sites were originally chosen on the basis of suitability for rice rather than diversified crops. This implies that about 85 percent of irrigated dry season land is suitable only for paddy (World Bank, 1985; p 50).

2.4.3 Rice Production and Contribution of Irrigation

Since rice is the principal crop grown on irrigated land in both wet and dry seasons, the econometric analysis of irrigation performance in Thai agriculture at the national level will be limited to rice production. On that basis, attention now will be focused on the past contribution of irrigation to rice production.

Table 2.9 suggests that higher rice productivity is associated with irrigated land.[8] Even though irrigation accounts for only 25 percent of total wet season rice area, it is associated with 40 percent of total rice production. Average rice yield on irrigated land during the past three decades is more than double yields on rainfed land. Dry season rice yield on irrigated land is especially significant: its average yield is almost 3 times

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[7] Government policy maintains domestic rice price at low levels because rice is the main determinant of the cost of living and the consumer's real income. This issue will be addressed in more detail in Section 2.5.

[8] Irrigation is often considered a land conserving technology. In other words, irrigation reduces the amount of land required for producing a given output. Notice that in this context, data on yield reflect the average productivity of the entire input package rather than just the influence of irrigation.

Table 2.9 Rainfed and Irrigated Rice Production, 1961-90

Area/Production/Yield	Average			
	1961-70	1971-80[a]	1981-90	1961-90[a]
Planted Area (1000 rai)				
Wet season paddy area[b]	43211	52271	59053	51511.7
Rainfed paddy area[c]	32478.6	40240.8	44444.1	31.54.5
Irrigated paddy area[d]	10732.4	12030.2	14608.9	12457.2
Irrigated area as % of total wet season area	24.8	23.0	24.7	24.2
Dry season paddy area[b]	n.a.	2481.3	4239	3457.8
Dry season area as % of total (wet+dry seasons) area	n.a.	4.5	6.7	6.3
Production (1000 ton of paddy rice)[e]				
Wet Season production[b]	10480	14535	17034	14016.3
Rainfed[c]	6222.3	9284.4	10162.4	8556.3
Irrigated[d]	4257.7	5250.6	6871.6	5460
Irrigated paddy production as % of total wet season paddy production	40.6	36.1	40.3	39.0
Dry Season production[b]	n.a.	1282.3	2397.2	1901.7
Dry season paddy production as % of total (wet+dry seasons) production	n.a.	8.1	12.3	11.9
Yield (kilogram/rai)				
Wet season	241.1	278.1	288.2	269.1
Rainfed	189.2	230.9	227.8	216.0
Irrigated	397.2	435.6	470.4	434.4
Dry season	n.a.	516.5	567.8	545.0

[a] Time series data for dry season starts in 1973.
[b] *Agricultural Statistics of Thailand*, MOAC. All rice areas in dry season are presumably irrigated.
[c] Calculated as residual i.e., total less irrigated.
[d] Irrigated Agriculture Branch, RID.
[e] Paddy rice production is rice production before threshing and milling (ratio of milled rice to paddy rice is approximately 0.65).

higher than normal yields on rainfed land in the wet season. These dramatic differences typically stem from the fact that most dry season rice is planted in a relatively small irrigated area which is adequately supplied by irrigation water and is well equipped with better water control and drainage systems. The security of reliable water control leads farmers to invest relatively more in modern inputs such as high yielding varieties and fertilizer, which usually results in substantially higher yields.

Apparently, the level of modern inputs used in Thai agriculture is still among the lowest in the world (FAO). The modern high yielding varieties (HYVs) of rice, i.e., the R.D (Rice Department) varieties, have not been very successful for the major wet season rice crop especially in rainfed areas. This is partly because the intensive technologies including heavy use of fertilizer, better water control and proper farm management are normally recommended for HYVs. Unfortunately, a policy environment that includes substantial rice export taxes and protection of the domestic fertilizer industry has discouraged such practices. On the other hand, the government has also adopted other policies that partially offset export taxes and protection of the fertilizer industry: irrigation water subsidies (to zero or near zero cost), rice farm price supports, cheap fertilizer programmes, etc.[9]

It is very difficult to determine the net effects of these various policy instruments. However, several relevant rice policies and implications for irrigation will be further discussed in the following section.

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[9] Numerous detailed analyses on Thai rice policies are available in the literature. See for example, Siamwalla et. al. (1990), Sicular (1989), and Feeney (1982).

2.5 Irrigation Water Management Policy

Irrigation water management in Thailand as elsewhere appears to fall into two broad categories, i.e., supply management and demand management.

2.5.1 Supply Management

As discussed earlier, major investments in large-scale irrigation projects dominated the Thai policy agenda for decades. During the first three National Economic and Social Development Plans (1961-66, 1967-71, and 1972-76, respectively), the highest priority in agriculture was placed on extensive large-scale irrigation development. During the 1960s and 1970s, irrigation works accounted for approximately 80 percent of all public investment in the agricultural sector. Nevertheless the performance of irrigation projects was questionable. It was widely recognized that thousands of farms in several irrigation service areas were unable to benefit from the systems due to early concentration on constructing major facilities and insufficient development of the distributional facilities.

During the Fourth Plan (1977-81), while new large-scale water resource development still continued, several small-scale irrigation projects were initiated largely in the Northeast where large-scale projects were not economically feasible. Along with constructing new dams and reservoirs, an attempt was also made to complete the distributional systems to ensure more efficient use of the existing irrigation systems. However, physical construction was emphasized to such a degree that administrative, operational and institutional problems were ignored. To date, farmers still perceive that irrigation systems belong to the government and it is the responsibility of the government to provide not only a sufficient supply of water but also to carry out maintenance work at all levels. In addition, since irrigation water is provided free of charge, most farmers receiving irrigation have viewed irrigation water as free and unlimited resource, so they do not economize in its use. This has made it even more costly for the government to supply irrigation water.

These limitations together with a decrease in agricultural prices have made large-scale irrigation projects unprofitable. As a result, the government during the Fifth and Sixth Plans (1982-86 and 1987-91, respectively) changed its focus to increasing development of medium- and small-scale multipurpose projects with greater emphasis on low income rainfed areas. Groundwater development projects have provided an alternative to surface irrigation. Of most importance, emphasis has been placed on encouraging local participation in irrigation development and management. These schemes are continuing under the current Seventh Plan (1992-96), and there is more attention to environmental consequences. Now an environmental impact assessment must accompany the planning for any water resource development project. In the Seventh Plan, water resources development has shifted from an individual project approach to a river basin approach in an effort to reduce conflicts among competing uses and to make effective uses of water resources at the macro level.

Obviously, the extensive expansion of irrigated area has reached its practical limit. As an alternative to supply expansion, the RID now emphasizes improvements in administration and operation of existing irrigation systems. Computerized systems of water scheduling and monitoring now assist in allocating water to different uses within large-scale projects. A program of institution strengthening, especially for Water User

Organizations, has also been emphasized. All these programs which aim at controlling water supply represent a prudent step towards increasing efficient use of irrigation water.

It is important to note that improving control of irrigation water supply is not only a means to increase efficiency of water use but also is a prerequisite to effective water pricing (Srivardhana, 1984; World Bank, 1985; and Asian Development Bank, 1986).

2.5.2 Demand Management

Inadequate control over the distribution of irrigation water supply is not entirely responsible for the poor performance of the existing public irrigation systems. The deterioration and low efficiency of these systems also stem partly from the peculiar nature of irrigation water supplies[10] and perhaps more importantly from the policy of fully subsidizing irrigation water. This policy primarily benefits wealthier farmers.

2.5.2.1 Pricing Instrument

Charges for irrigation water use have never been imposed in the public irrigation system. The policy has somehow been justified on the basis of equity. The legal basis for cost recovery of irrigation systems was first provided in the Public Irrigation Act of 1942. The maximum fee that could be collected from users was raised from 0.50 baht/rai to 5 baht/rai in 1964 when the Act was amended. These proposed fees have never actually been levied due to political difficulties. Only small fees have been imposed on industries using irrigation water. Moreover these proposed fees are extremely low and outdated.

Although no direct charges for irrigation services provided by the RID have been levied on farmers, for many years the government maintained substantial taxes on rice

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[10] This issue will be addressed in greater details in the next chapter.

exports. Accordingly, many have argued that irrigation subsidies (i.e., government provision of irrigation at zero cost) are partially offset by this export tax, the so called rice premium.[11] The rice premium was first introduced in 1956 as a source of government revenue and finally abolished in 1986 due to depressed world prices. The premium rates varied by grade of export rice and were intended primarily to maintain artificially low and stable rice prices for domestic consumers. During the first 10 year period of 1956-1966, the rice premium was as high as 40 percent of export prices which implied a tax of slightly over 80 percent of the farm gate prices. Thereafter the premium rates gradually declined until finally abolished.

Since there is some correlation between the benefits from irrigation and surplus from rice production, using export taxes or other taxes on marketed output as a method of cost recovery for irrigation investment does target in part the beneficiaries of irrigation. However, this does not imply that output taxation is a substitute for irrigation fees. By depressing the farm level price of rice, the rice export premium tended to increase the relative profitability of other crops; and to some extent this would encourage crop diversification. Similarly, irrigation water charges would encourage diversification since rice requires considerably more water than do alternative crops with the exception of sugarcane (Doorenbos and Pruitt, 1977).

However, a tax on output cannot be a substitute for irrigation water fees unless irrigation water is always used in fixed proportion with other inputs. In other words, a

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[11] The rice premium was levied on rice exported to world markets. Basically, it was used as a flexible tool of market intervention to achieve a variety of objectives: keeping domestic prices low, improving the terms of trade for Thailand, and raising government revenues.

tax on output generally does not alter the proportions between water and other inputs in production so that marginal returns to water are equal to opportunity costs. Output taxes cannot be a substitute for user fees in achieving an efficient allocation of water.

Of course, in a second best economy with many distortions, it is not clear that an optimal policy involves pricing irrigation water to farmers at its marginal cost or marginal return in alternative use. Nevertheless, it seems clear that zero user fees for irrigation water is not part of an optimal second best policy because it fails to encourage conservation of water by farm users.

Charges for irrigation water is a controversial and highly political issue. There have been several legislative attempts to amend the Irrigation Act for higher irrigation charges, but those have been unsuccessful including the recent attempt in 1992. The 1992 proposal would increase irrigation water fees for agricultural water uses to 15 baht per rai for wet season cultivation, 20 baht per rai for dry season, and 30 baht per rai for agricultural activities that use irrigation water for the entire year.

Despite political failure in legislating irrigation water fees, many economists consider water pricing schemes as the best means of increasing irrigation efficiency and financing irrigation projects. In Thailand, rapid economic growth in recent years has led not only to a significant increase in total demand for water but also to more intense conflicts among competing uses. As a supplement to other methods, water pricing has frequently been identified as a means to encourage more proper use of water resources. As Sethaputra et al., argue,

> Water pricing is critical for meeting water shortages and managing growing demands...it helps determine the optimal sectoral allocation of

> water...it encourages reduction of waste and promotes efficient water use, thereby limiting demand, and it recovers the cost of supply, thereby making funds available for expanding the supply...Shielding the users from rising supply price of water guarantees either growing water shortages, growing water subsidies or a combination of the two (Setraputra et, al., 1990; p 17).

The intention of the government to collect irrigation fees was again stated in the current Seventh Plan. Charges are suggested to cover only operating and maintenance costs of the irrigation system in order to induce more efficient use of water.

2.5.2.2 Quantity Control Instrument

In the absence of user fees, quantity controls have implicitly or explicitly been employed to ration the supply of irrigation water between farms. Explicit quantity controls are often adopted during periods of drought. The general approach has been to set a target for the dry season cropping area reduction, generally referred to as the dry season area reduction or the DSAR approach. Unfortunately, inadequate water for irrigation in the dry season seems to continue even during periods of normal rainfall. The problem appears to be more severe in the Central region due to the rapid growth of demand for water in other competing uses.

In theory price and quantity controls may be substitutes in achieving on efficient allocation of water resources (e.g., see Baumol and Oates, 1988 for an introduction to the extensive literature on price versus quantity controls for achieving efficient levels of resource use or pollution). Nevertheless the effects of price and quantity controls may differ substantially in practice. The optimal mix of price and quantity controls may depend largely on the particular institutions. These issues deserve a comprehensive analysis which is beyond the scope of this study.

2.6 Summary

This chapter has provided an overview of irrigation development and irrigated agriculture in Thailand. The main conclusions are as follows.

In the past, agricultural growth in Thailand has been achieved mainly through land expansion (largely by clearing forest land) rather than by yield increases. However, future expansion of land is no longer possible due to high environmental costs involved. Yield increases appear to be the only alternative for bringing about agricultural growth.

Crop diversification from rice has been experienced, but it has occurred primarily on rainfed land rather than irrigated land. Rice is the principal crop grown on irrigated land for both wet and dry seasons, accounting for 88 and 60 percent of irrigated area in the wet and dry season, respectively.

There have been substantial investments in irrigation systems following the World War II. Despite extensive investments, irrigated area presently accounts for only 20 percent of the total agricultural land. Moreover only 13 and 5 percent of the total agricultural land actually benefits from irrigation facilities in the wet and dry season, respectively. Agricultural growth through extensive expansion of irrigated area is now limited due to rising construction and environmental costs.

The provision of zero or near zero charges for irrigation water supplies represents an important subsidy to the agricultural sector. Given rapid economic growth in Thailand, the related issues of water pricing and efficient use of irrigation water will be of growing importance in the future.

Chapter 3. Theoretical Framework

3.1 Introduction

This chapter provides a basic theoretical framework for the study. It discusses the derivation of the implicit value of irrigation water and evaluation of the impacts of irrigation in agricultural production. The concept of market failure in irrigation water supplies is first discussed. This suggests that a decentralized market pricing system which reflects the marginal value of water will not normally exist to allocate water among uses. Then various methodologies for evaluating the economic value of irrigation water are presented. The theoretical and empirical literature related to the valuation of irrigation water is reviewed. Then static theoretical models for estimating water values and evaluating the impacts of irrigation are discussed both within a primal framework (a crop production function) and a dual framework (a system of input demand and output supply relations).

3.2 Market Failure in Irrigation Water Supplies

It has been well recognized that irrigation water has several physical and economic attributes that lead to market failure and inefficiency. As noted by Young and Haveman (1985), water is a fugitive resource flowing from one property to another. This makes it difficult to establish and enforce property rights. By its nature, irrigation water is accessible to many users but belongs to no one until it is withdrawn and put to use. In principle property rights can in effect be established through a system of metering water to users, but in practice this is impossible on irrigation systems serving many small holdings. Even when property rights are established through communal management, the cost of effective enforcement is relatively high.

Scarcity of water resources implies that water consumption by one farmer reduces the possibilities for consumption by others. Since the amount of water is relatively limited, especially in the dry season, this suggests that irrigation water takes on a positive economic value. In this case, the absence of property rights can generate market failure.

Irrigation water resource development usually exhibits economies of scale where relatively high investment is needed in building physical facilities, conveyance, and distributional systems. In addition, costs of water storage and extensive delivery systems (such as canals, ditches and dikes) from control regulators to farm turnouts tend to be high. These indivisible costs are not variable with the amount of water consumed. Obviously, the marginal cost of supplying irrigation water to an additional user is low compared to average cost. Thus, even if marginal cost pricing leads to an efficient allocation of water, it cannot fully finance irrigation projects. Even though economists have proposed the use of water markets to improve the allocative efficiency of water resource (Weinberg, Kling, and Wilen, 1993), irrigation water is seldom allocated through the market mechanism in the same manner as other resources and commodities.

3.3 Economic Value and Pricing of Irrigation Water

In most countries irrigation water supplies are publicly provided and highly subsidized. Users are often charged only for the cost of transferring water from its source to the farm or cost of control and distribution. However, even these costs often have been subsidized.

If there was sufficient water to satisfy all users at a zero price, then any positive price would unduly restrict water use. However, such circumstances certainly do not prevail in Thailand at present. Scarcity should be reflected in user costs if water is to be used efficiently. In the absence of market prices, irrigation water supplies can be valued using either a cost or benefit approach.[1]

3.3.1 Cost Based Approach

A conventional pricing rule is that price should be equal to marginal cost. However, in industries such as irrigation with decreasing average costs, marginal cost pricing would result in substantial losses since overheads will not be covered. Unless the government subsidizes losses, marginal cost pricing of irrigation water cannot be expected from a private enterprise. In contrast average cost pricing would permit firms supplying irrigation water to avoid losses, but this would exclude some users who would be willing to pay the marginal cost, i.e., average cost pricing would unduly restrict the use of water.

3.3.2 Benefit Based Approach

In contrast to the cost based approach, irrigation water can also be valued on the basis of benefits obtained from using irrigation water supplies (at the margin benefits and costs should be equal). The most two common methods include the residual valuation approach and the estimation of a production function.

The residual imputation approach is based on two major assumptions. First, the market prices of all other inputs except the one to be valued are equal to its marginal value product. Secondly, the total value of output can be divided into shares such that each input is paid according to its marginal productivity, i.e., the total value of output is

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[1] Several approaches can be used to derive an economic value of irrigation water. More extensive discussions on economic rates of irrigation water can be found in, for example, Ansari (1968); Young and Haveman (1985); Gibbons (1986); and Chaudhry and Young (1990).

equal to cost of production when factor prices equal marginal value products at equilibrium. It is well known from Euler's theorem that this condition holds if the production function is constant returns to scale.

The residual imputation concept used to value irrigation water supplies can be mathematically expressed as

$$TVP = \sum_{i=1}^{n-1} MVP_i X_i + MVP_n X_n \tag{3.1}$$

where TVP represents the total value product of a given output. X_i represents the i^{th} input ($i=1,...,n-1$) and MVP_i denotes the known marginal value product or wage of input i. The irrigation water supply and its marginal value product are represented by X_n and MVP_n, respectively.

From (3.1), the shadow price of irrigation water or the residual attributable to water can then be computed using farm budget studies. Mathematical programming can also be employed to derive the imputed value of irrigation water. However, programming studies have emphasized determination of the optimal allocation of a given water supply to irrigated crops rather than deriving the economic value of water. Nonetheless the implicit value of irrigation water is indicated by the solution to the dual corresponding to the water scheduling problem. Recent empirical studies that explicitly address valuation of irrigation water using mathematical programming are in Bernado et al. (1988) and Chaudhry et al. (1990).

As noted by Young et al. (1985), the residual imputation approach has serious limitations. The assumptions of static profit maximization and a constant returns to scale production function are restrictive. Moreover, if one or more variable inputs are omitted, the economic value of irrigation water derived from the residual approach will be exaggerated. Qualitative inputs affecting crop production such as managerial ability are likely to be omitted in such computations. In this respect, the residual return to irrigation water may be overstated.

As an alternative to the residual imputation approach, valuation of irrigation water is also commonly based on econometric estimates of production functions. The marginal physical product of irrigation water is calculated as a first derivative of the estimated production function. Under certain conditions this can provide a measure of the marginal value of irrigation water. Numerous studies of water production functions have been conducted by agronomists and soil scientists within the framework of controlled field experiments.

Yaron (1971) made a distinction between seasonal and dated crop water production functions. The seasonal water production function relates yield to quantity of water used during the growing season assuming optimal sequencing of water application over time. The dated water production function is more complicated because it takes into account the dynamic response at each instant during the growing period (Hexem and Heady, 1978). In other words, yield depends on the time and method of application as well as the quantity of water.

The dynamic crop response function or dated production function typically is expressed as either an additive or multiplicative function over time. The additive production function (Moore, 1961) assumes that crop yield in each period is relatively independent, i.e., a serious water deficit in one period only influences crop growth during that period. This assumption is often very restrictive.

A multiplicative production function over time permits an interaction of water use for different periods in the determination of final crop outputs. Pioneering works on multiplicative dated production functions are by Hall and Butcher (1968), Jensen (1968) and Hanks (1974). The time framework considered is often arbitrary and has frequently been chosen to coincide with the physiological growth stage or sometimes as a weekly or monthly interval. There are at least two water variables that are commonly used in the development of water production functions: evapotranspiration[2] or relative evapotranspiration (Jensen, 1968; Doorenbos and Kassam, 1979; and Rao, 1988) and irrigation depth or total (volume of) field water supply (Stewart and Hagan, 1973; and Gulati and Murty, 1979).

A generalized water production function was developed by Hexem and Heady (1978). Using experimental data, the yield responses to water were estimated in interaction with fertilizer applications and dummy variables representing variations in climate and soil types. Doorenbos and Kassam (1979) utilized available information from locations worldwide to quantify the effects of water stress on several crops. Relative yield is specified as a function of relative evapotranspiration or the ratio of water deficit, which varies with climate. They emphasized that other variables which interact with

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[2] Conceptually, crop evapotranspiration is the actual water or moisture required for crop growth, comprising two relevant parts, i.e., the amount of water evaporated from soil surface and the water transpired by the plant. The value of maximum water requirement for each crop (crop potential evapotranspiration-ET_p) usually depends on several climatic factors such as sunshine duration, wind speed, relative humidity, etc. Several methods can be used in determining ET_p (see Doorenbos and Pruitt,1977).

water in determining crop yield are not incorporated into the relationship; so the equation is valid only for high yielding varieties that are well adapted to the environment and are grown in large fields under optimal agronomic practices and adequate supply of all inputs.

Relatively few empirical studies of water production functions have been done by economists. A major problem in such cases is obtaining an accurate measure of water consumption. For instance, water as measured by the number of irrigations in the crop year assuming an average of three inches per irrigation was employed in estimating the value productivity of irrigation water in Pakistan using farm survey data (Hussain, 1985). A recent economic study of crop water production functions using survey data was presented by Kulshreshtha, Schuetz, and Brown (1991). They estimated seasonal water production functions for several crops in Saskatchewan agriculture. The water variable used in the model was inches of seasonal water application, i.e., the sum of rainfall and irrigation water. Fertilizer and dummy variables representing differences in location, farm size, field size and type of irrigation were included in the models.

In the irrigation literature, generalized water production functions are often developed in order to model intraseasonal or interseasonal optimal allocation of water. Given estimates of water response functions, marginal analysis or mathematical programming is subsequently employed to simulate the optimal quantity of water use for irrigated crops over the entire season or within discrete time intervals during the planning period. Relatively few studies explicitly analyze the value of irrigation water.

3.4 Theoretical Economic Model

3.4.1 Conceptual Basis

In the present study, estimates of a static production function (primal approach) and a system of input demand and output supply equations (dual approach) are used to compute the economic value of irrigation water. The impacts of irrigation on levels of output and variable inputs are also derived. This section briefly discusses three fundamental conceptual difficulties with these approaches. These problems are measurement of irrigation water use, importance of location and timing, and social versus private valuation of water.

3.4.1.1 Problems of Measuring the Water Variable

Obtaining an accurate measure of irrigation water used in crop production is extremely difficult. Even in controlled experiments, losses from deep percolation, seepage, and evaporation pose some difficulties in measuring water use. Since controlled experiments generally are not feasible in economic research, water consumption is often approximated in empirical studies (see for example, Hussain, 1985).

Data on water use was not available in the present study. As a consequence, irrigation productivity or the shadow price of irrigation water in this study will generally be approximated by the difference between irrigated and non-irrigated land productivities. However, it is worth reemphasizing that the productivity of irrigated land is likely to reflect not only the water supplies made available by irrigation facilities but also the superior quality of (irrigated) land. Nevertheless data are not available to differentiate the impacts of those two components of productivity for irrigated land. As a result, estimates of marginal value of irrigation water could be inflated, especially in the case of inferences from national time series data.

3.4.1.2 Marginal Productivity of Irrigation Water in Relation to Location and Timing

Crop production functions can be expected to vary greatly with climate, rainfall, and soil fertility. Moreover, the marginal productivity of irrigation water presumably is also sensitive to the levels of other inputs such as soil nutrient levels, quantity and quality of seed, labour, and management skills.

Due to these physical complexities of the site specific crop response to water application, the performance of irrigation systems may be best evaluated as a project study approach at the farm level. In the present study, the farm level analysis or micro analysis of irrigation water value is conducted using a static production function framework.[3] Cross section farm survey data on agricultural production at the particular irrigation project is employed as a case study analysis where the economic value of irrigation water is explicitly derived from the estimated crop production functions.

Even though the contribution of irrigation water may be best assessed at a micro level, such an analysis for a particular location is unlikely to be representative for the nation. Consequently it is also useful to conduct an analysis using data aggregated at the national level in spite of inevitable problems due to aggregation. The national or macro analysis is based on secondary time series data.

In addition to spatial variation in impacts of irrigation water, crop response to

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[3] Although a dynamic or dated production function is more realistic than a static model, a dynamic production function is not estimated here. Complexities of the biological crop growth process in each environmental condition make it very difficult to accurately model dynamic process in empirical studies (Kulshreshtha et al., 1991).

irrigation also varies with rainfall and its seasonal distribution. As a result, the marginal value of irrigation will be estimated separately for both wet and dry growing seasons in farm level and national level analyses.

3.4.1.3 Private and Social Values of Irrigation Water

As was discussed in Chapter 2, input and output prices in Thai agriculture are subjected to extensive distortions through government intervention. As a consequence, market prices for both inputs and outputs may not reflect their social opportunity costs or values. The principal example is government stabilization policies in the Thai rice market where rice farm prices have been maintained below world price levels. In contrast, several measures such as import quotas and price supports have raised soybeans prices above market equilibrium levels. Fertilizer and irrigation subsidies also distort input markets.

Since no attempt has been made to correct for these distortions in the present analysis, the marginal values of irrigation water calculated here are estimates of private rather than social values of irrigation, i.e., these are estimates of farmers' willingness to pay for irrigation (within a static framework). The net effect of extensive price distortions on the difference between private and social values of irrigation is not clear and beyond the scope of this study.

3.4.2 Primal Approach: Econometric Estimation of Crop Production Function

As discussed earlier, specification of a crop production function may permit assessment of marginal returns to irrigation water. Unfortunately, data on amount of water consumption is not available at the macro level and cannot be obtained with any accuracy from interviews at the farm level in the present study. As a result in the case of macro data, the productivity of irrigation water will be approximated as the difference between the productivities of irrigated and non-irrigated land. In addition, the impacts of irrigation on levels of outputs and variable inputs can be calculated within the static framework. The methodology can be outlined as follows.

3.4.2.1 Private Marginal Value of Irrigation Water

Let Y = f(X, Ia, Ta) be a concave production function where a vector of variable inputs (X) are employed in producing a single output (Y) given irrigated land (Ia) and total agricultural land (Ta) as quasi-fixed inputs. Assuming static competitive profit maximizing behaviour, a farmer solves the following short-run maximization problem (conditional on Ia, Ta)

$$\max_{X} \ \pi \equiv P\, f(X,Ia,Ta) - WX \tag{3.2}$$

where output and input prices are represented by P and W, respectively. Solving (3.2), the first-order conditions (FOC) for an interior solution are

$$P\ \partial f(X^{*},Ia,Ta)/\partial X - W = 0 \tag{3.3}$$

The corresponding variable input demand (X^*) and the output supply (Y^*) equations are

$$X^{*} = X(P,W,Ia,Ta) \tag{3.4}$$

$$Y^{*} = Y(P,W,Ia,Ta) \tag{3.5}$$

and in turn short-run profits are

$$\pi(P,W,Ia,Ta) \equiv P\, f\,(X\,(P,W,Ia.Ta),Ia,Ta) \\ -WX\,(P,W,Ia,Ta) \tag{3.6}$$

Differentiating (3.6) with respect to irrigation land Ia (with total land Ta constant)

$$\partial\pi(P,W,Ia,Ta)/\partial Ia = P\ \partial f(X^*,Ia,Ta)/\partial Ia + P\ [\partial f(X,Ia,Ta)/\partial X - W]\partial X^*/\partial Ia \tag{3.7}$$

and substituting the FOC for profit maximization (3.3) yields

$$\partial\pi(P,W,Ia,Ta)/\partial Ia = P\ \partial f(X^*,Ia,Ta)/\partial Ia \tag{3.8}$$

This result (3.8) is an application of the static envelope theorem (e.g., Takayama, 1985). Thus the net benefit associated with converting a unit of non-irrigated land to irrigation is equal to the difference between the marginal value product of irrigated and non-irrigated land, evaluated at the equilibrium level of inputs X^*.

However, it must be reemphasized that the economic value or the shadow price of irrigation water to the farmer can be computed as the marginal value product of irrigation water (as in (3.8)) only when static short-run competitive profit maximization holds. The relation between this shadow price and corresponding shadow prices under dynamic equilibrium and/or risk aversion is discussed in the next chapter.

3.4.2.2 Impacts of Irrigation on Output and Variable Input

The effects of an additional unit of irrigation on equilibrium levels of output and variable inputs can also be calculated from estimates of the production function. The impacts of irrigation on output and variable inputs can be computed from the partial derivatives of the FOC with respect to the quasi-fixed input, Ia (Lau, 1976).

For example, total differentiating the FOC (3.3) with respect to Ia yields

$$P\, f_{X\,X}\ \partial X^{*}/\partial Ia\ +\ P\, f_{X\,Ia}\ =\ 0 \tag{3.9}$$

and in turn (assuming f_{XX} has an inverse)

$$\partial X(P,W,Ia,Ta)/\partial Ia\ =\ -[f_{X\,X}(X^{*},Ia,Ta)]^{-1}.\ f_{X\,Ia}(X^{*},Ia,Ta) \tag{3.10}$$

The effect of irrigation on output can be calculated simply as

$$\partial Y(P,W,Ia,Ta)/\partial Ia\ =\ f_{X}(X^{*},Ia,Ta)\ \partial X^{*}/\partial Ia\ +\ f_{Ia}(X^{*},Ia,Ta) \tag{3. 11}$$

It should be noted that the numerical solution for the impacts of irrigation on output and inputs using this approach can only be derived when the production function is non-linear, i.e., $f_{XX}(\cdot)$ is nonzero.

3.4.3 Dual Approach: Restricted Dual Profit Function

The shadow price of irrigation water and impacts of irrigation on output and inputs can be evaluated within a dual framework as well as a primal framework.

3.4.3.1 Private Marginal Value of Irrigation Water

A restricted dual profit function is defined by the following short-run competitive profit maximization problem conditional on Ia and Ta:

$$\pi(P,W,Ia,Ta)\ =\ \max_{X}\ PY-WX \quad s.t.\ \ F\ (Y,X,Ia,Ta)\ =\ 0 \tag{3.12}$$

where $\pi(\cdot)$ represents a restricted dual profit function or short-run profit function when quasi-fixed inputs such as irrigated land and total land (Ia and Ta, respectively) are present. $F(Y,X,Ia,Ta)=0$ denotes a continuous transformation function relating multioutputs (Y), variable inputs (X), Ia and Ta. Input and output prices are denoted by W and P, respectively.

Properties of the dual profit function ($\pi(\cdot)$) are well known (see for example, Chambers, 1988, Varian, 1992). By applying Hotelling's lemma, the system of estimating equations for variable input demands and output supplies conditional on quasi-fixed inputs can be derived as follows:

$$X_i(P,W,Ia,Ta) = -\partial\pi(P,W,Ia,Ta)/\partial W_i \quad i=1,\ldots,n \tag{3.13}$$

$$Y_j(P,W,Ia,Ta) = \partial\pi(P,W,Ia,Ta)/\partial P_j \quad j=1,\ldots,m \tag{3.14}$$

Static competitive profit maximization implies, in addition to Hotelling's lemma, that the profit function (π) is linear homogeneous and convex in prices P, W. In turn (3.13)-(3.14) are homogeneous of degree zero in prices P, W and satisfy restrictions corresponding to a symmetric positive semi-definite Hessian matrix of π in P, W. These restrictions (plus monotonicity) correspond locally to the hypothesis of static competitive short-run profit maximization.

In order to estimate the shadow price of irrigation water ($\partial\pi(\cdot)/\partial Ia$), two different approaches can be employed. First, the profit function $\pi(P,W,Ia,Ta)$ can be estimated simultaneously with the input demand and output supply equations ((3.13) and (3.14)). The shadow price of irrigation water can then be inferred directly from the estimated $\pi(\cdot)$ equation simply by differentiating the profit function with respect to Ia:

$$\partial\pi(P,W,Ia,Ta)/\partial Ia \equiv W_{iw} \tag{3.15}$$

where W_{iw} represents the shadow price or the economic value of irrigation water associated with the conversion of one unit of non-irrigated to irrigated land at the margin.

Alternatively, the shadow price of irrigation water can be derived directly from estimates of the system of input demand and output supply equations ((3.13) and (3.14)). In this case, the shadow price of water can be calculated as

$$\begin{aligned}\partial\pi(P,W,Ia,Ta)/\partial Ia = {} & P\partial Y(P,W,Ia,Ta)/\partial Ia \\ & -W\partial X(P,W,Ia,Ta)/\partial Ia\end{aligned} \tag{3.16}$$

In principle the two approaches lead to the same results for the shadow price of irrigation water ($\partial\pi/\partial Ia$), although there are differences between the two approaches in terms of econometric estimation (hence the two approaches will provide different consistent estimates of the shadow price) and hypothesis testing. The advantage of the second approach is that it does not necessarily require direct estimation of the profit function. Direct estimation of this function may not be feasible due to the large number of coefficients in this equation relative to equations for derivatives of the function.

An advantage of the dual approach is that the conditions for static competitive short-run profit maximization behaviour can be tested more easily than in the primal approach. The behavioral hypothesis implies the following symmetry or reciprocity conditions (for integrability):

$$-\partial X_i(P,W,Iw)/\partial W_j = -\partial X_j(P,W,Iw)/\partial W_i \tag{3.17}$$

$$\partial Y_j(P,W,Iw)/\partial P_i = \partial Y_i(P,W,Iw)/\partial P_j \tag{3.18}$$

$$-\partial X_i(P,W,Iw)/\partial P_j = \partial Y_j(P,W,Iw)/\partial W_i \tag{3.19}$$

These symmetry conditions are easily tested by standard methods. Testing of homogeneity and convexity conditions is also possible but is more problematic (Clark and Coyle, 1994).

Note that calculation of the shadow price for irrigation in the primal approach (3.8) depends critically upon this behavioral hypothesis. In contrast, calculation of the shadow price for irrigation by the dual approach as in (3.16) depends less critically on this hypothesis: output supply and input demand equations can be estimated (without imposing reciprocity) even if the behavioral hypothesis is rejected.

3.4.3.2 Impacts of Irrigation on Output and Variable Input

In contrast to the primal approach, calculation of the impacts of irrigation on levels of outputs and inputs is relatively straightforward within the dual framework. The impacts of irrigation on output ($\partial Y^*(P,W,Ia,Ta)/\partial Ia$) and on variable inputs ($\partial X^*(P,W,Ia,Ta)/\partial Ia$) can be inferred directly from the estimated output supply and input demand equations ((3.13)-(3.14)).

3.4.4 Optimal Allocation of Irrigation Water in Static and Dynamic Models

This section summarizes relations between shadow prices for water at different time periods assuming an optimal allocation of water over time. Both static and dynamic models of resource allocation are considered.

3.4.4.1 Static Analysis

Consider a two-period model for the profit maximizing competitive farm-firm in static equilibrium. All prices are given and known with certainty in both periods. The firm seeks to maximize the present value of profits over the two periods given an initial stock of water W_0:

$$\begin{aligned} \underset{(X,WU)}{Max\,\pi} &= \pi_1 + \frac{1}{1+r}\pi_2 \\ s.t. \quad & WU_1 + WU_2 \leq W_0 \end{aligned} \tag{3.20}$$

where $\pi_i = p_i\ f_i(X_i, L, L \cdot WU_i) - w_i X_i$, p_i and w_i represent output price and vector of variable input prices (i=period 1,2), and r is the discount rate. The crop production function is denoted by $f_i\ (\cdot)$. X, L, WU represent vector of variable inputs, land (quasi-fixed) input and irrigation water use per unit of land, respectively. Note that for simplicity there are no costs (in terms of evaporation or storage) to deferring water use to the second period.

Suppose that the production function is differentiable in WU and there is an interior solution for WU ($WU_i^* > 0$, i=1,2). The first order conditions include

$$\begin{aligned} \partial\pi_1/\partial WU_1 &= \frac{1}{1+r}\partial\pi_2/\partial WU_2 \quad \Rightarrow \\ p_1\ \partial f_1/\partial WU_1 &= \frac{1}{(1+r)}p_2\ \partial f_2/\partial WU_2 \end{aligned} \tag{3.21}$$

Given that irrigation water is provided at zero cost, the profit maximizing firm would allocate water such that the equilibrium marginal value product of irrigation water in the first period is equal to the discounted equilibrium marginal value of irrigation water in the second period. This implies that the marginal value (shadow price) of irrigation water in the two periods would differ only by the rate of interest.

If storage costs are significant, then the relation (3.21) is modified simply as follows: discounted marginal returns net of storage costs are equal between time periods assuming an optimal allocation of water and differentiability of the production function. This result also extends in an obvious manner to dated production function where crop output depends on timing as well as quantity of water applications. For example, consider a static model analogous to (3.20) but with 365 periods rather than two periods. Suppose that the production function is differentiable. Then, for any time periods where positive amounts of irrigation water are used in the optimal plan, the discounted marginal value products of irrigation water are equal.

Thus the key assumption in deriving the relation (3.21) between the shadow prices of water for different time periods given an optimal allocation scheme is that the production function is differentiable with respect to water use, However, the realism of the assumption is not clear. Although crop response generally is modelled in terms of differentiable production functions, it has also been suggested that yield plateaus and nonsubstitution of nutrients may arise when a nutrient is below a critical level (see Paris for a discussion of the von Liebig hypothesis). Perhaps such reasoning applies to water as well as nutrients.

Nondifferentiability of crop production functions with respect to water seems most likely to arise in the context of a dated production function, when plants are most sensitive to moisture stress during formation of the reproductive organs and flowering (De Datta, 1981). Economists have occasionally assumed that critical levels of water are required at various stages of plant growth, and that impacts of water above the critical levels at these stages may be negligible. For example, Yaron et al. specified crop yield as a function of the number of critical days (defined as the number of days with moisture below a critical level) for each stage of plant growth. However, there is little empirical knowledge regarding dated production functions (Vaux and Pruitt, 1983; Kulshreshtha et al.). Moreover it has been argued that such models by economists are contradicted by present knowledge in agronomy (Vaux and Pruitt).

3.4.4.2 Dynamic Analysis

An illustration of a dynamic irrigation water management problem is

$$\begin{aligned} \max_{\{X(t),WU(t)\}} & \int_{t=0}^{T} \{p\, f(X_t, WU_t L, L) - wX_t\} e^{-rt} dt \\ s.t. \quad & \dot{W}_t = R_t - WU_t - \delta W_t \\ & W(0) = W_0 \end{aligned} \tag{3.22}$$

Here R_t= amount of rainfall in period t, δ= rate of depreciation of the water stock (e.g., percolation, evaporation and seepage), W_t= water stock per unit of land in period t, W_0= initial stock of water, X_t= level of variable inputs in t, WU_t= level of water use in period t per unit of irrigated land, and L= amount of irrigated land (constant over t).

Define the current value Hamiltonian

$$H_t^c = p\, f(X_t, WU_t L, L) - wX_t + \lambda_t (R_t - WU_t - \delta W_t) \tag{3.23}$$

where λ_t is the current value shadow price of the stock of irrigation water. Dynamic maximization implies

$$(a)\quad \frac{\partial H^c}{\partial X_t} = 0$$

$$(b)\quad \frac{\partial H^c}{\partial WU_t} = L\ P\ \frac{\partial f}{\partial WU_t} - \lambda_t = 0$$

$$(c)\quad \dot{W}_t = \frac{\partial H^c}{\partial \lambda_t} \tag{3.24}$$

$$(d)\quad \dot{\lambda}_t = \quad r\lambda_t - \frac{\partial H^c}{\partial W_t} \quad = r\lambda_t + \delta\lambda_t$$

$$\frac{\dot{\lambda}_t}{\lambda_t} = r+\delta$$

The percentage change in the current value shadow price along the optimal path is r+δ. This is similar to the result for the static model, where it was assumed that the rate of evaporation from the reservoir equals zero (δ=0). This result depends on the assumption that (i) the transition equation is linear in (or independent of) the stock of water W_t, and (ii) the objective function f (·) is independent of W_t.

3.5 Summary

In this chapter, several physical and economic attributes of irrigation water were highlighted. The resulting market inefficiency and the apparent increasing scarcity of water serve as the rationale for an empirical study of the economic value of irrigation in agricultural production. Various approaches employed in valuing irrigation water supplies have been reviewed. The static primal approach (based on direct estimation of a production model) and the dual approach (based on estimation of a system of input demand and output supply equations) can provide frameworks for estimating the marginal value of water or irrigated land and evaluating impacts of irrigation of levels of outputs and inputs.

Chapter 4. A Comparison of Shadow Prices in Static and Dynamic Models

4.1 Introduction

The general methodology for calculating shadow prices for resource stocks in static models is well understood. For example, assuming a competitive profit maximizing firm in static equilibrium, the shadow price of irrigated land (benefits to the firm of a marginal increase in the stock of irrigated land) is equal to the equilibrium marginal value product of irrigated land. Under the same assumptions the shadow price of irrigation water is equal to the equilibrium marginal value product of irrigation water. These results can be viewed most generally as an application of the static envelope theorem. This envelope theorem can be applied to specify shadow prices of resource stocks in a wide variety of static models (e.g., under noncompetitive behaviour or risk aversion and uncertainty).

However an analogous methodology has not been developed for calculating shadow prices in dynamic models, even though resource management problems are often viewed more appropriately in a dynamic than static setting. Dynamic envelope theorems have only been developed recently (Caputo 1990 a,b,c; LaFrance and Barney). Caputo has shown that the primal-dual method of analyzing comparative static properties of static models extends in a relatively simple manner to dynamic optimal control models. This generalizes the envelope theorem from a static to a dynamic setting. However, when the parameter to be perturbed is an argument of a transition equation, these dynamic envelope theorem results are expressed in terms of Lagrange multipliers for transition equation constraints in the dynamic problem. Since static envelope theorem results for the risk-neutral firm are not generally expressed in terms of Lagrange multipliers, these formulations of dynamic envelope theorems for the firm obscure to some extent the relation between static and dynamic envelope theorems. In turn this obscures to some extent the relation between shadow prices in static and dynamic models.

The first purpose of this chapter is to develop dynamic envelope theorem results that provide an alternative measure of shadow prices when the parameter to be perturbed is an argument of a transition equation. These results define shadow prices in terms of derivatives of objective function and transition equation terms along an optimal path without any reference to Lagrange multipliers. This helps to clarify relations between shadow prices in static and dynamic models. These dynamic envelope theorem results are derived by a relatively simple modification of the primal-dual methodology of Caputo. The second purpose of this chapter is to illustrate applications of envelope theorems in several highly simplified theoretical static and dynamic models of the firm that can be related to management of irrigation.

This chapter is organized as follows. First, application of the well known static envelope theorem is illustrated for several general static models (competitive behaviour under risk neutrality, and risk aversion). Second, dynamic envelope theorems are discussed: Caputo's results are summarized, and then his methodology is extended to provide alternative measures of shadow prices when parameters are arguments in transition equations. Third, dynamic envelope theorems are applied to several dynamic models of the firm with irrigation (competitive behaviour under risk neutrality and risk version). Fourth, specifications for the purposes of econometric estimation of the dynamic models considered here are discussed briefly. Fifth, conclusions from the dynamic envelope theorem results are drawn within the context of modelling the shadow price to the firm of irrigated land and irrigation water.

4.2 Static Models

4.2.1 Risk Neutrality

Assume a single period production function $y_t = f(x_t, L_t, WU_t \cdot L_t)$, where y_t=crop output in period t, x_t =vector of variable inputs in t, L_t=land input (irrigated) in t, and WU_t=water use in t per unit of irrigated land. Here it is assumed that current period output y_t depends on current period water use per acre WU_t but not on lagged water use $WU_{t-1},\ldots,WU_{t-s}$.

Suppose that the firm is in a static, competitive profit maximizing equilibrium conditional on a fixed amount of irrigated land and water per acre, i.e., the firm solves the following maximization problem:

$$\pi(p,w,L_t,WU_t) = \max_{x\geq 0} p\, f(x_t,L_t,WU_t \cdot L_t) - wx_t \tag{4.1}$$

where p =output price, w =vector of variable input prices, and $\pi(p,w,L_t,WU_t)$ denotes the corresponding dual profit function. The shadow price of an additional unit of irrigated land is

$$\begin{aligned}\partial\pi(p,w,L_t,WU_t)/\partial L &= p\ \partial f\,(x_t^*,L_t,TWU_t)/\partial L \\ &\quad + pWU_t\ \partial f\,(x_t^*,L_t,TWU_t)/\partial TWU\end{aligned} \tag{4.2}$$

where x_t^* is the solution to problem (4.1), and total water use is denoted as TWU_t $(TWU_t \equiv WU_t \cdot L_t)$. The shadow price of an additional unit of water per acre of irrigated land is

$$\partial\pi(p,w,L_t,WU_t)/\partial WU = p\ \partial f\ (x_t^*,L_t,WU_t{\cdot}L_t)/\partial WU \tag{4.3}$$

Both of these results are obtained by applying the standard static envelope theorem to the profit maximization problem (4.1) (e.g., Takayama). These results can be derived assuming either that the initial levels (L_t,WU_t) are positive or zero. If initial (L_t,WU_t) are zero, then the results can be established directly from standard first order conditions for an interior solution $x_t^*>>0$ to (4.1) (Samuelson). If initial (L_t, WU_t) are positive, then these results follow from the standard primal-dual analysis of model (4.1) (Hatta; Silberberg).

Substituting (4.3) into (4.2),

$$\begin{aligned}\partial\pi(p,w,L_t,WU_t)/\partial L = {} & p\ \partial f\ (x_t^*,L_t,TWU_t)/\partial L \\ & +(WU_t\ /L_t)\ \partial\pi(p,w,L_t,WU_t)/\partial WU\end{aligned} \tag{4.4}$$

The first term on the right hand side of (4.2) and (4.4) is the equilibrium marginal value product of the land holding total water use TWU constant, i.e., it is the equilibrium marginal value product of an additional unit of land that is not irrigated (or, more precisely, does not change total water use). In sum, we are interested in measuring the marginal value (shadow price) of an additional unit of irrigation water rather than the marginal value of an additional unit of land per se. Thus (4.3) provides an appropriate measure of the shadow price of irrigation, and (4.4) indicates that the shadow price of additional irrigated land overstates the shadow price of irrigation if $\partial f(x_t^*,L_t,TWU_t)/\partial L >0$, i.e., if the marginal product of nonirrigated land is positive.

The above results indicate that shadow prices for irrigation and for irrigated land are measured essentially in terms of equilibrium marginal value products. This is the standard intuitive approach to measuring the value of irrigation to farmers in static models. However, it is important to note that these results depend critically upon the assumption of static competitive profit maximization as in (4.1).

Alternatively suppose that water use has a multiperiod effect on crop production. Then the production function should be represented as $y_t = f(x_t, L_t, WU_t \cdot L_t, WU_{t-1} \cdot L_t, \ldots, WU_{t-s} \cdot L_t)$ where the application of water in a particular period influences production over a total of s periods. Then the static envelope theorem implies that the shadow price equation (4.3) is modified as follows:

$$\partial\pi(\cdot)/\partial WU_t = p \sum_{u=0}^{s-1} (1/1+r)^u \, \partial f\,(x^*_{t+u}, L_t, WU_{t+u} \cdot L_t)/\partial WU_{t+u} \qquad (4.5)$$

where r denotes a discount rate.

4.2.2 Risk Aversion

Suppose that there is uncertainty regarding parameters of the model (e.g., water use or output price) and the firm is not risk neutral. For example the firm may choose variable inputs x in period t so as to maximize expected utility from the random variable profits π, where profits are random due to uncertainty regarding WU_t. Then instead of (4.1) the firm solves

$$V(p, w, L_t, q_t) = \max_{x \geq 0} EU[p\, f(x_t, L_t, WU_t \cdot L_t) - wx_t] \qquad (4.6)$$

where q_t= vector of moments for the random variable WU_t, and EU denotes the expectations operator ($EU(\pi) \equiv \int_s \pi(s)\phi(s)ds$ for probability $\phi(s)$ of $\pi(s)$). Then the static envelope theorem implies that the shadow price for additional irrigated land is measured as follows rather than as in (4.2):

$$\partial V(p,w,L_t,q_t)/\partial L = \partial EU[p\ f(x_t^*,L_t,WU_t \cdot L_t)]/\partial L \tag{4.7}$$

In order to simplify the above result, assume a linear mean-variance utility function $U = E\pi - (\alpha/2)V\pi$ where $E\pi$, $V\pi$ denote mean and variance of profits, respectively, and α is the coefficient of absolute risk aversion. Also assume a Just -Pope technology $y = a(x,L) + b(x,L)^{1/2}\varepsilon$, where $\varepsilon = (WU - EWU)\cdot L$. The mean and variance of the random variable WU are EWU and VWU, respectively, so $E\varepsilon = 0$, $V\varepsilon = VWU\ L^2$. In turn the mean and variance of output are $Ey = a(x,L)$, $Vy = b(x,L)L^2 VWU$. Then the expected utility maximization problem reduces to

$$V(p,w,L_t,q_t) = \max_{x \geq 0} p\ a(x,L_t) - wx - (\alpha/2)p^2 b(x,L)L^2 VWU \tag{4.8}$$

Applying the static envelope theorem, the shadow price for additional irrigated land is

$$\begin{aligned}\partial V(p,w,L_t,q_t)/\partial L = p\ \partial a(x_t^*,L_t)/\partial L - (\alpha/2)p^2\ \partial b(x_t^*,L_t)/\partial L\ L_t^2\ VWU \\ -\alpha p^2\ b(x_t^*,L_t)L_t\ VWU\end{aligned} \tag{4.9}$$

In the case of risk neutrality ($\alpha = 0$), this reduces to (4.2) for a Just-Pope technology.

4.3 Dynamic Envelope Theorems

The static envelope theorem has recently been generalized to optimal control models by Caputo and by LaFrance and Barney. Caputo demonstrates that the static primal-dual analysis extends to optimal control models in an obvious manner, and this leads to a dynamic envelope theorem. A brief summary of Caputo's results is presented here. It is useful to distinguish between two cases where the exogenous parameter of interest (e.g., irrigated land L) does and does not enter a transition equation. Then new dynamic envelope theorems are developed for the case where parameters are arguments of transition equations.

4.3.1 Transition Equation Is Independent of Parameters (Caputo)

The dynamic primal-dual analysis is simplest when the parameter of interest does not enter a transition equation. This case is developed in Caputo (1990a). For example consider the general optimal control problem

$$\begin{aligned} J(\beta,x_0) &= \max_{\{u(t)\}} \int_{t=0}^{\tau} F(x,\dot{x},u,t;\beta)dt \\ s.t.\quad \dot{x}(t) &= g(x,u,t) \\ x(0) &= x_0\ \ x(t) \geq 0 \quad \forall\, t \end{aligned} \tag{4.10}$$

where x is a vector of state variables, u is a vector of control variables, $\dot{x}(t) \equiv \partial x(t)/\partial t$ and β is the vector of exogenous parameters (excluding the initial levels of the state variables, x_0) that are time independent (e.g., exogenous prices p,w are assumed to be constant over the horizon t=0,...,τ). The important assumption here is that the parameters β do not enter the transition equations $\dot{x}(t)=g(x,u,t)$.

A distinction between the state variable(s) x_0 and parameters β can be made in the context of resource management models. x_0 can be defined as the initial level of a capital input or resource stock which can be depleted through use or augmented by decisions endogenous to the model. This includes the case of irrigation water. In contrast, β

consists of a set of parameters that are not altered by processes endogenous to the model. This includes prices that are exogenous to the firm, and it can also include resource stocks whose levels are treated as exogenous to the firm. Since this thesis is directly concerned with the management of water rather than land, it is useful to abstract from issues such as soil erosion and treat land as a fixed input. In sum, x_0 can be defined as the total stock of water in the firm's irrigation system (per unit of irrigated land), and β can include the total amount of irrigated land for the firm.

Define the primal-dual

$$G(\beta,x_0,X) = J(\beta,x_0) - \int_{t=0}^{\tau} F(x,\dot{x},u,t;\beta)dt \tag{4.11}$$

where $X \equiv \{(x(t),\dot{x}(t),u(t))\}$, i.e., X denotes a path for the endogenous variables over $0<t<\tau$. Suppose that X_A solves problem (4.10) given (β_A ,x_{0A}). Then (4.10)-(4.11) implies that

$$\begin{aligned} &(a) \quad G(\beta_A,x_{0A},X_A) = 0 \\ &(b) \quad G(\beta,x_{0A},X_A) \geq 0 \quad \textit{for all } \beta \end{aligned} \tag{4.12}$$

The inequality follows from the fact that X_A is feasible for a problem (4.10) conditional on x_{0A}, irrespective of β. This fact depends on the assumption that β does not enter the transition equation. Equation (4.12) implies that β_A solves the following minimization problem

$$\min_{\beta} G(\beta,x_{0A},X_A) \quad \Rightarrow \beta^* = \beta_A \tag{4.13}$$

Assuming that $\beta_A >> 0$ (i.e., all elements of the vector β_A of exogenous parameters for the optimal control problem (4.10) are nonzero), then (4.13) implies standard first and second order conditions for an interior minimum:

$$\partial G(\beta_A, x_{0A}, X_A)/\partial\beta = 0 \tag{4.14}$$

$$[\partial^2 G(\beta_A, x_{0A}, X_A)/\partial\beta\partial\beta] \text{ symetric positive semidefinite} \tag{4.15}$$

If the dimension of β is Mx1, then (4.14) provides M first order conditions and the dimension of the Hessian matrix in (4.15) is MxM.

Evaluating (4.14) for an element β_i of β implies, by (4.11),

$$\partial J(\beta, x_0)/\partial\beta_i = \int_{t=0}^{\tau} \partial F(x^*(t), \dot{x}^*(t), u^*(t), t; \beta)/\partial\beta_i \, dt \tag{4.16}$$

where $\{(x^*(t), \dot{x}^*(t), u^*(t))\}$ denotes the path of the endogenous variables at solution to the optimal control problem (4.10). The proof of this dynamic envelope theorem is formally identical to the proof of the static envelope theorem by the primal-dual method (Hatta; Silberberg). Moreover the result is very similar to the static envelope theorem when parameters do not enter constraints (e.g., Hotelling's Lemma). In both cases the objective function is differentiated with respect to the exogenous parameter holding the levels of endogenous variables constant at their equilibrium levels, but the objective function is defined for a single period in the static case and over multiple periods in the dynamic case.

One difference in practice between these static and dynamic envelope theorems is that the change in the state variables ($\dot{X}$) is often omitted from the objective function in static models but included in the objective function of dynamic models (typically as costs of adjustment). However, in principle the change in state variables can also be included in the objective function of a static model (as a parameter rather than as an endogenous variable); so static and dynamic envelope theorems need not differ in this respect.

4.3.2 Transition Equation Is Not Independent of Parameters (Caputo)

An essential distinction between static and dynamic envelope theorems arises when the transition equation is not independent of parameters. The optimal control problem (4.10) can be modified as follows:

$$\begin{aligned} J(\beta,x_0) &= \max_{\{u(t)\}} \int_{t=0}^{\tau} F(x,\dot{x},u,t;\beta)dt \\ s.t. \quad \dot{x}(t) &= g(x,u,t;\beta) \\ x(0) &= x_0 \quad x(t)\geq 0 \quad \forall\, t \end{aligned} \tag{4.17}$$

In contrast to (4.10), the transition equation depends on parameters β: $\dot{x}(t)=g(x,u,t;\beta)$. This somewhat complicates the primal-dual analysis. For example, if the primal-dual is defined as in (4.11) then (4.12b) no longer holds because X_A generally is no longer feasible for all β (β influences the transition equation and hence the feasible set for X). In turn (4.13)-(4.16) would no longer hold.

A primal-dual analysis of (4.17) is developed by Caputo (1990b). Define the primal-dual for (4.17) as

$$G(\beta,x_0,X) = J(\beta,x_0) - \int_{t=0}^{\tau} F(x,\dot{x},u,t;\beta)dt \qquad (\beta,x_0,X)\in S \tag{4.18}$$

where the set S consists of all (β,x_0,X) satisfying the transition equations $\dot{x}(t)=g(x,u,t;\beta)$, initial conditions $x(0)=x_0$, and $x(t)\geq 0$ for all t. If X_A solves (4.17) given (β_A,x_{0A}), then $G(\beta_A,x_{0A},X_A)=0$ and $G(\beta,x_{0A},X_A)\geq 0$ for all β such that $(\beta,x_{0A},X_A)\in S$. Thus β_A solves

$$\min_{\beta\in S(x_{0A},X_A)} G(\beta,x_{0A},X_A) \Rightarrow \beta^*=\beta_A \tag{4.19}$$

where $\beta\in S(x_{0A},X_A)$ is equivalent to the restriction $(\beta,x_{0A},X_A)\in S$. Expressing these restrictions in Lagrange form, problem (4.19) implies that β_A solves

$$\begin{aligned}\min_{\beta} H(\beta,x_{0A},X_A,\lambda_A) \equiv J(\beta,x_{0A}) &- \int_{t=0}^{\tau} F(x_A(t),\dot{x}_A(t),u_A(t),t;\beta)dt \\ &- \int_{t=0}^{\tau} \lambda_A(t)[g(x_A(t),u_A(t),t;\beta)-\dot{x}_A(t)]dt \\ &- \int_{t=0}^{\tau} \eta_A(t)x_A(t)dt\end{aligned} \tag{4.20}$$

where λ_A is the path $\{\lambda(t)\}$ at solution for the Lagrange multipliers of the transition equations $\dot{x}(t)=g(x,u,t;\beta)$ when the optimal control problem (4.17) (or the corresponding Hamiltonians) are expressed in Lagrange form. Similarly η_A is the path $\{\eta(t)\}$ at solution for the Lagrange multipliers of constraints $x(t)\geq 0$ for all t. Since $\eta_A(t)x_A(t)=0$ for all t and does not have β as an explicit argument, the term $\int_{t=0}^{\tau}\eta_A(t)x_A(t)dt$ in (4.20) can be ignored in further primal-dual analysis. Integrating $\int_{t=0}^{\tau}\lambda_A(t)\dot{x}_A(t)dt$ by parts $[d(\lambda x)/dt=\dot{\lambda}x+\dot{x}\lambda \Rightarrow \lambda(\tau)x(\tau)-\lambda(0)x(0)=\int\dot{\lambda}(t)x(t)dt+\int\dot{x}(t)\lambda(t)dt)$ and substituting into (4.20),

$$\min_{\beta} H(\beta,x_{0A},X_A,\lambda_A) \equiv J(\beta,x_{0A}) - \int_{t=0}^{\tau} F(x_A(t),\dot{x}_A(t),u_A(t),t;\beta)dt$$
$$- \int_{t=0}^{\tau} \lambda_A(t)g(x_A(t),u_A(t),t;\beta)dt - \int_{t=0}^{\tau} \dot{\lambda}_A(t)x_A(t)dt + \lambda_A(\tau)x_A(\tau) - \lambda_A(0)x_A(0) \tag{4.21}$$

Then, proceeding as in (4.14)-(4.15), $\beta_A >> 0$ implies

$$\partial H(\beta,x_{0A},X_A,\lambda_A)/\partial\beta = 0 \tag{4.22}$$

$$[\partial^2 H(\beta_A,x_{0A},X_A,\lambda_A)/\partial\beta\partial\beta] \text{ symmetric positive semidefinite} \tag{4.23}$$

The first order conditions establish a dynamic envelope theorem:

$$\partial J(\beta,x_0)/\partial\beta_i = \int_{t=0}^{\tau} \partial F(x^*(t),\dot{x}^*(t),u^*(t),t;\beta)/\partial\beta_i \, dt$$
$$+ \int_{t=0}^{\tau} \lambda^*(t)\partial g(x^*(t),u^*(t),t;\beta)/\partial\beta_i \, dt \tag{4.24}$$

A dynamic envelope theorem result can also be obtained for the initial level of the state variable, $x_0>0$. Modify the above Lagrange H(·) (4.20) to $\tilde{H}(\beta,x_{0A},X_A,\lambda_A,\lambda_{0A})$ by subtracting the term $\lambda_{0A}(x_{0A}- x(0))$ from the right hand side of (4.20), where λ_{0A} is the equilibrium value of the Lagrange multiplier corresponding to the constraint $x(0)=x_0$ in the optimal control problem (4.17). Then, proceeding as in (4.14)-(4.15), $x_{0A}>0$ implies $\partial\tilde{H}(\beta,x_{0A},X_A,\lambda_A,\lambda_{0A})/\partial x_0=0$ and in turn

$$\partial J(\beta,x_0)/\partial x_0 = \lambda_0^* \tag{4.25}$$

i.e., the shadow price of x_0 is equal to the equilibrium value of the corresponding

Lagrange multiplier.

Equation (4.24) indicates that the dynamic envelope theorem is much more complex than the static envelope theorem when the parameter β_i enters a transition equation. In this case, the marginal impact of β_i on the value of the firm's objective function depends in large part on the equilibrium marginal impact of β_i on the transition equations, weighted by equilibrium values of Lagrange multipliers for the transition equations. The magnitudes of these multipliers may be difficult to approximate from static models.

4.3.3 An Alternative Approach: X Or $\dot{X}$ Enters the Objective Function

A simple modification of Caputo's primal-dual analysis can provide additional insight into envelope theorems and shadow prices when exogenous parameters enter transition equations. Consider the optimal control problem (4.17) where parameters β and of course x_0 influence transition equations. Note that, given the initial level of state variable(s) x_0 and transition equations $\dot{x}(t)=g(x(t),u(t),t;\beta)$ for all t, the time path of state variable(s) x (and hence $\dot{x}$) over all t is determined by the time path of the controls u over all t. In other words, x(s) and $\dot{x}(s)$) are determined by the choice of controls u over the interval t=(0,...,s), given x_0 and β. This relation can be written in compact form as $x_t=\psi_1(U_t,x_0,\beta,t)$ and $\dot{x}_t=\psi_2(U_t,x_0,\beta,t)$, where $U_t=(u_0,...,u_t)$ and $\psi_2(\cdot)=g(\psi_1(\cdot),u_t,t;\beta$. If x or $\dot{x}$ are arguments of the objective function term $F(\cdot)$, then the optimal control problem (4.17) can be rewritten as

$$J(\beta,x_0) = \max_{\{u(t)\}} \int_{t=0}^{\tau} F\{\psi_1(U_t,x_0,\beta,t),\psi_2(U_t,x_0,\beta,t),u_t,t;\beta\}\ dt \qquad (4.26)$$
$$s.t. \quad \psi_1(\cdot) \geq 0 \quad \forall\ t$$

where substituting $\psi_1(U_t,x_0,\beta,t)$ for x_t and $\psi_2(U_t,x_0,\beta,t)$ for $\dot{x}_t$ in the objective function term $F(x_t,\dot{x}_t,u_t,t;\beta)$ in effect restricts the feasible set $\{(u(t),x(t),\dot{x}(t))\}$ to satisfy the constraints $\dot{x}(t)=g(x(t),u(t),t;\beta)$ for all t and $x(0)=x_0$.

However it is important to note that the substitution in (4.26) is valid only if x or $\dot{x}$ enters into the objective function term F(·) for problem (4.17). If $\partial F(\cdot)/\partial x=0$ and $\partial F(\cdot)/\partial \dot{x}=0$, then the choice of {u(t)} for (4.26) is in effect unconstrained by the transition equations and x_0. F(·) does depend on x and $\dot{x}$ in the standard dynamic theory of the competitive firm with adjustment costs, where both the state variable capital and net (or gross) investment enter directly into the objective function. On the other hand, there are many problems where x and $\dot{x}$ are not arguments of F(·). This is the case in dynamic irrigation models considered below.

Suppose that x and $\dot{x}$ are arguments of F(·). Then define the primal-dual

$$G(\beta,x_0,U) = J(\beta,x_0) - \int_{t=0}^{\tau} F\{\psi_1(U_t,x_0,\beta,t),\psi_2(U_t,x_0,\beta,t),u_t,t;\beta\}dt \qquad (4.27)$$

where $U\equiv u(t)$, i.e., U denotes a path for the endogenous variables u over $0<t<\tau$. The term $-\int_{t=0}^{\tau}\eta^*(t)\psi_1(U_t,x_0,\beta,t)dt$ where $\{\eta^*(t)\}$ are equilibrium levels of Lagrange multipliers for the constraints $\psi_1(\cdot)\geq 0 \ \forall$ t in (4.26), can also be included on the right hand side of (4.27), and $G \equiv G(\beta, x_0, U, \eta^*)$. However, assuming $\eta^* >> 0$ (inequality constraints $x(t) \geq 0$ are never binding at solution to a problem (4.17)), adding this term to (4.27) would not change results of the following primal-dual analysis.

Suppose that $X_A \equiv \{(x(t), \dot{x}(t), u(t))\}_A$ solves problem (4.17) given (β_A, x_{0A}) or equivalently U_A solves problem (4.26) given (β_A, x_{0A}). Then (4.26)-(4.27) imply

$$\begin{aligned} &(a) \quad G(\beta_A, x_{0A}, U_A) = 0 \\ &(b) \quad G(\beta, x_0, U_A) \quad \geq 0 \quad \textit{for all } (\beta, x_0) \end{aligned} \tag{4.28}$$

The inequality follows from the fact that (a) U_A is feasible for a problem (4.26) irrespective of (β, x_0), and (b) the substitution of $\psi_1(\cdot)$ and $\psi_2(\cdot)$ for x and $\dot{x}$ in (4.27)implies that the path(s) $\{(x(t), \dot{x}(t))\}$ implicit in the integral $\int F(\cdot)dt$ for (4.27) are feasible for the specified (U, β, x_0) and the transition equations. This is true even though β as well as x_0 enter the transition equations. Equation (4.28) implies that (β_A, x_{0A}) solves the following minimization problem

$$\min_{\beta, x_0} G(\beta, x_0, U_A) \quad \Rightarrow (\beta, x_o)^* = (\beta_A, x_{0A}) \tag{4.29}$$

and in turn (given $(\beta_A, x_{0A}) >> 0$)

$$\partial G(\beta_A, x_{0A}, U_A)/\partial\beta = 0 \tag{4.30}$$

$$\partial G(\beta_A, x_{0A}, U_A)/\partial x_0 = 0 \tag{4.31}$$

$$\partial^2 G(\beta_A, x_{0A}, U_A)/\partial\beta\partial x_0 \quad \textit{symetric positive semidefinite} \tag{4.32}$$

where (4.32) refers to the Hessian matrix of $G(\beta_A, x_{0A}, U_A)$ with respect to β and x_0.

The first order conditions (4.30)-(4.31) imply the following dynamic envelope theorem results:

$$\begin{aligned}\partial J(\beta, x_0)/\partial\beta_i &= \int_{t=0}^{\tau} dF(x^*(t), \dot{x}^*(t), u^*(t), t; \beta)/\partial\beta_i \, dt \\ &+ \int_{t=0}^{\tau} dF(x^*(t), \dot{x}^*(t), u^*(t), t; \beta)/\partial x_t \; \partial\psi_1(U_t^*, x_0, \beta, t)/\partial\beta_i \, dt \\ &+ \int_{t=0}^{\tau} dF(x^*(t), \dot{x}^*(t), u^*(t), t; \beta)/\partial\dot{x}_t \; \partial\psi_2(U_t^*, x_0, \beta, t)/\partial\beta_i \, dt\end{aligned} \tag{4.33}$$

$$\begin{aligned}\partial J(\beta, x_0)/\partial x_0 &= \int_{t=0}^{\tau} dF(x^*(t), \dot{x}^*(t), u^*(t), t; \beta)/\partial x_t \; \partial\psi_1(U_t^*, x_0, \beta, t)/\partial x_0 dt \\ &+ \int_{t=0}^{\tau} dF(x^*(t), \dot{x}^*(t), u^*(t), t; \beta)/\partial\dot{x}_t \; \partial\psi_2(U_t^*, x_0, \beta, t)/\partial x_0 dt\end{aligned} \tag{4.34}$$

where $\{(x^*(t), \dot{x}^*(t), u^*(t))\}$ denotes the path of the endogenous variables at solution to the optimal control problem (4.17) or equivalently (4.26). The envelope relations (4.33) reduce to Caputo's result (4.16) when parameters β do not enter the transition equations, i.e., $\partial\psi_1(\cdot)/\partial\beta = 0$ and $\partial\psi_2(\cdot)/\partial\beta = 0$.

When parameters β do enter the transition equations, then (4.33) presents an alternative to Caputo's result (4.24). Equation (4.24) defines $\partial J(\beta, x_0)/\partial\beta$ in terms of derivatives of the objective function term $F(\cdot)$ and transition equation $g(\cdot)$ along the equilibrium path, and Lagrange multipliers λ^* for the transition equation along the optimal path. In contrast, Equation (4.33) defines $\partial J(\beta,x_0)/\partial\beta$ in terms of derivatives of the objective function term $F(\cdot)$ along the optimal path and in terms of derivatives of the functions $\psi_1(\cdot)$ and $\psi_2(\cdot)$ relating $\{x(t)\}$ and $\{\dot{x}(t)\}$ to the equilibrium control vector $\{u^*(t)\}$, x_0 and β. In principle the functions $\psi_1(\cdot)$ and $\psi_2(\cdot)$ can be constructed directly from knowledge of transition equations $\dot{x}(t)=g(x(t),u(t),t;\beta)$. Thus an essential difference between the two dynamic envelope theorems, from the viewpoint of approximating $\partial J(\beta,x_0)/\partial\beta$, is that (4.24) requires approximation of the equilibrium path for both controls $\{u^*(t)\}$ and Lagrange multipliers $\{\lambda^*(t)\}$ for transition equations; whereas (4.33) requires approximation of the equilibrium path for controls but not for Lagrange multipliers.

The initial level of the state variable, x_0, always influences the transition equations. An earlier result (4.25) related the shadow price $\partial J(\beta,x_0)/\partial x_0$ to a Lagrange multiplier. In contrast, Equation (4.34) relates this shadow price to derivatives of the objective function term $F(\cdot)$ along the optimal path and to derivatives of the functions $\psi_1(\cdot)$ and $\psi_2(\cdot)$ relating $\{x(t)\}$ and $\{\dot{x}(t)\}$ to the equilibrium control vector $\{u^*(t)\}$, x_0 and β. This result clarifies that the general idea of the static envelope theorem extends to the dynamic shadow price for x_0, with certain modifications.

4.3.4 An Alternative Approach: X And $\dot{X}$ Do Not Enter the Objective Function

Now suppose that the state variables and rate of change in the state variables $(x,\dot{x})$ are not arguments of the objective function term $F(\cdot)$. Then the analysis (4.26)-(4.34) is no longer valid. However, an alternative modification of Caputo's primal-dual analysis of static models is valid, given that some control variables (denoted as u) are arguments of F(·). This approach will be developed next.

In contrast to the previous section, the transition equations and initial conditions for the optimal control problem (4.17) are used to define the path for the control variable {u(t)} as a function of parameters (β,x_0) and the paths of other endogenous variables $\{(x(t),\dot{x}(t))\}$. The transition equations $\dot{x}(t)=g(x(t),u(t),t;\beta)$ can be inverted as follows (assuming $\partial g(\cdot)/\partial x \neq 0$ for all x):

$$u(t) = \phi(x(t),\dot{x}(t),t;\beta) \tag{4.35}$$

This result implies that, for any $\{(x(t),\dot{x}(t))\}$ and β, there exists a corresponding {u(t)} (assuming elements of u can be negative) such that $\{(x(t),\dot{x}(t),u(t))\}$ satisfies initial conditions (β, x(0)) and transition equations.

Equations (4.35) can also be used to indicate certain changes in feasible paths $\{(x(t),\dot{x}(t),u(t))\}$ in response to changes in initial conditions (β,x_0). Given a particular path $\{x(t)\}_f$ that is feasible for an optimal control problem (4.17) conditional on a particular $(\beta,x_0)_A$, there exists a corresponding path $\{u(t)\}_f$. If the parameters β change and the particular path $\{x(t)\}_f$ was to remain unchanged, then there would be a compensating change in {u(t)}. This relation between feasible u, x, $\dot{x}$ and β is specified by (4.35).

If u_t is an argument in the objective function for the optimal control problem and the transition equation is invertible in x, then (4.17) implies the following calculus of variations problem:

$$J(\beta,x_0) = \max_{\{(x(t)\}} \int_{t=0}^{\tau} F\{x_t,\dot{x}_t,\phi(x_t,\dot{x}_t,t;\beta),t;\beta\}\ dt \qquad (4.36)$$
$$s.t. \quad x(0) = x_0$$
$$\phi(\cdot) \geq 0 \quad \forall t$$

where $\phi(\cdot)$ is substituted for u_t in $F(\cdot)$. The restriction $\phi(\cdot) \geq 0$ can be dropped from (4.36) if $u_t < 0$ is feasible. Provided that u_t is an argument of $F(\cdot)$, this substitution in effect restricts the maximization problem in (4.36) to the feasible set $\{(u(t),x(t),\dot{x}(t))\}$ satisfying the transition equations $\dot{x}_t=g(x_t,u_t,t;\beta_A)$ and $x(0)=x_{0A}$. Thus solutions to problems (4.36) and (4.17) are equal if u_t is an argument of $F(\cdot)$.

Define the primal-dual

$$G(\beta,x) = J(\beta,x_0) - \int_{t=0}^{\tau} F\{x_t,\dot{x}_t,\phi(x_t,\dot{x}_t,\beta,t),t;\beta\}\ dt \qquad (4.37)$$

where $X \equiv \{x(t)\ \forall\ t\}$. The possible inequality constraints $\phi(\cdot) \geq 0\ \forall\ t$ $(u(t) \geq 0\ \forall\ t)$ can be ignored in defining the primal-dual by the same reasoning as in (4.27). Given parameters (β_A, x_{0A}), let $\{(x_A(t),\dot{x}_A(t),u_A(t))\}$ denote a solution to the optimal control problem (4.17). Then (4.36)-(4.37) imply

$$(a) \quad G(\beta_A,X_A) = 0$$
$$(b) \quad G(\beta,X_A) \geq 0 \quad \textit{for all } \beta \qquad (4.38)$$

The equality (a) is obvious. In order to show (b), note that

$$J(\beta,x_0) = \int_{t=0}^{\tau} F\{x(t)^*,\dot{x}(t)^*,\phi(x(t)^*,\dot{x}(t)^*,\beta,t),t;\beta\}\ dt \qquad (4.39)$$

by (4.36) where $\{(x(t)^*, \dot{x}(t)^*, u(t)^*\}$ solves (4.16) given (β, x_0), and

$$\int_{t=0}^{\tau} F\{x(t)_A, \dot{x}(t)_A, \phi(x(t)_A, \dot{x}(t)_A, \beta, t), t; \beta\}\, dt \tag{4.40}$$

is a feasible value of the objective function for (4.36) given (β, x_{0A}). If feasible u are restricted to be non-negative, then the restriction $\phi(\cdot) \geq 0$ is satisfied by requiring β to be in the neighbourhood of β_A. Equation (4.38) implies that β_A is a global solution to the following minimization problem

$$\min_{\beta} G(\beta, X_A) \;\; \Rightarrow \;\; \beta^* = \beta_A \tag{4.41}$$

and in turn (given $\beta_A >> 0$)

$$\partial G(\beta_A, X_A)/\partial\beta \; = 0 \tag{4.42}$$

$$\partial^2 G(\beta_A, X_A)/\partial\beta\partial\beta \quad \textit{symmetric positive semidefinite} \tag{4.43}$$

The first order conditions (4.42) imply the following dynamic envelope theorem results:

$$\begin{aligned} \partial J(\beta, x_0)/\partial\beta_i \; &= \int_{t=0}^{\tau} \partial F(x^*(t), \dot{x}^*(t), u^*(t), t; \beta)/\partial\beta_i \, dt \\ &+ \int_{t=0}^{\tau} \partial F(x^*(t), \dot{x}^*(t), u^*(t), t; \beta)/\partial u_t \;\; \partial\phi(x_t^*, \dot{x}_t^*, \beta, t)/\partial\beta_i \, dt \end{aligned} \tag{4.44}$$

where $\{(x^*(t), \dot{x}^*(t), u^*(t)\}$ denotes the path of the endogenous variables at solution to the optimal control problem (4.17) or equivalently (4.36). The envelope relations (4.44) reduce to Caputo's result (4.16) when parameters β do not enter the transition equations, i.e., $\partial\phi(\cdot)/\partial\beta = 0$.

The above primal-dual analysis can also be extended to the case of a change in the parameter x_0. Given parameters (β_A, x_{0A}), let $\tilde{X}_A \equiv \{(x(t), \dot{x}(t)) \ \forall \ t>0\}$ denote a solution to the calculus of variations problem (4.36). Construct the primal-dual $G(\beta, x_0, \dot{x}_0, \tilde{X}) \equiv J(\beta, x_0) - \int_{t=0}^{T} F(x_t, \dot{x}_t, \phi(x_t, \dot{x}_t, \beta, t), t; \beta) dt$. As in (4.38b) evaluate G($\cdot$) for a change in parameter x_0 from x_{0A} with $\tilde{X}$ constant at solution $\tilde{X}_A$ given (β_A, x_{0A}). Then the change in $\dot{x}_0$ must be the negative of the change in x_0. Thus $G(\beta_A, x_{0A}, \dot{x}_{0A}, \tilde{X}_A) = 0$ and $G(\beta_A, x_{0A} + \Delta x_0, \dot{x}_{0A} - \Delta x_0, \tilde{X}_A) \geq 0$ for all Δx_0. In turn $\partial G(\beta_A, x_{0A} + \Delta x_0, \dot{x}_{0A} - \Delta x_0, \tilde{X}_A)/\partial(\Delta x_0)|_{\Delta x_0 = 0} = 0$.

However, essentially the same relation can be derived directly from the following Hamilton-Jacobi equation for the optimal control problem (4.17):

$$-\partial J(\beta, x_0)/\partial t = \max_u F(x_0, \dot{x}_0, u, 0; \beta) + \partial J(\beta, x_0)/\partial x_0 \;\; g(x, u, 0; \beta) \qquad (4.45)$$

where u_0^* at solution to (4.17) also solves (4.45). Assuming an interior solution $u_0^* >> 0$ for (4.45) and F($\cdot$), g($\cdot$) are differentiable in u, the first order conditions for a solution to (4.45) yield

$$\partial F(x_0, \dot{x}_0, u_0^*, 0; \beta)/\partial u + \partial J(\beta, x_0)/\partial x_0 \;\; \partial g(x_0, u_0^*, 0; \beta)/\partial u = 0 \qquad (4.46)$$

This provides a simple solution for the shadow price $\partial J(\cdot)/\partial x_0$ in terms of derivatives of

F(·) and g(·) with respect to u, evaluated at the first period solution $(x_0,\dot{x}_0,u_0)^*$.

4.4 Dynamic Models with Irrigation

The above discussion indicates how the specification of the transition equation(s) influences calculations of shadow prices for irrigation in dynamic models. As before the crop output production function may be specified as $y_t = f(x_t,L_t,WU_t\cdot L_t)$, where y_t= crop output in period t, x_t= vector of variable inputs in t, L_t= land input (irrigated) in t, and WU_t= water use in t per unit of irrigated land. Costs of adjustment internal to the firm can also be incorporated by specifying $\dot{WU}_t$ or $\dot{L}_t$ as arguments of the production function.

The initial stock of water per unit of irrigated land is $W(0) = W_0$. The transition equation for the stock of water per unit of irrigated land can be specified as either

$$\dot{W}(t) = g(W(t),WU(t),t) \tag{4.47}$$

or

$$\dot{W}(t) = g(W(t),WU(t),t;L(t)) \tag{4.48}$$

In the first case the amount of irrigated land L(t) does not influence the equation of motion for the stock of water per unit of irrigated land, so the shadow price of irrigated land $(\partial J(\cdot)/\partial L)$ can be calculated as in (4.16). In the second case, where L does enter the equation of motion for the stock of water per unit of irrigated land, the shadow price of irrigated land is calculated in a more complex manner as in (4.24), (4.33) or (4.44). The shadow price of the initial stock of water W_0 can be calculated as in (4.34) or (4.46).

4.4.1 Shadow Prices Under Certainty When the Transition Equation is Independent of Irrigated Land

Suppose that all parameters are known by the firm with certainty, and define the following optimal control problem:

$$
\begin{aligned}
J(p,w,W_0,L,R,r) &= \max_{\{(x(t),WU(t))\}} \int_{t=0}^{\tau} \{pf(x_t,L,WU_t\cdot L)-wx_t\}\, e^{-rt}dt \\
s.t.\ \ \dot{W}_t &= R_t - WU_t - \delta W_t \\
W(0) &= W_0
\end{aligned}
\qquad (4.49)
$$

Here R_t= contribution of rainfall in period t to stock of water, δ= rate of depreciation (evaporation) of the stock, and R= $(R_0,\ldots,R_\tau)$. For simplicity, costs of adjustment are not specified.

In this model the transition equation for the stock of water per unit of irrigated land is specified as independent of the amount of irrigated land as in (4.47). In other words, the amount of irrigated land available to the firm can be increased without directly reducing the stock of water per acre of irrigated land. This in turn assumes that (a) there are no economies or diseconomies of scale (as measured in irrigated acres) regarding the transition equation at the firm level, and that (b) the irrigation facility operates so as to provide a constant flow of water per unit of irrigated land irrespective of the number of acres irrigated by the firm. Assumption (a) regarding the transition equation at the firm level may be a reasonable approximation. However assumption (b) regarding the rules of operation for the irrigation facility may often be violated, i.e., the initial amount of irrigation water provided by the irrigation facility per acre of irrigated land may often decrease with the amount of land irrigated by the firm. Thus the transition equation in the above model or more generally (4.47) should be viewed as conditional on particular rules of operation for the public irrigation facility.

This transition equation in model (4.49) implies that the shadow price of irrigated land can be calculated as in the dynamic envelope theorem (4.16):

$$\begin{aligned} \partial J(p,w,W_0,L,R,r)/\partial L &= \int_{t=0}^{T} p \; \partial f(x^*(t),L,TWU^*(t))/\partial L \; e^{-rt}dt \\ &+ \int_{t=0}^{T} p \; \partial f(x^*(t),L,TWU^*(t))/\partial TWU \;\; WU^*(t) \; e^{-rt}dt \end{aligned} \tag{4.50}$$

where $TWU^*(t) \equiv WU^*(t) \cdot L$. The first integral on the right hand side of the above shadow price equation (where total water use TWU is held constant as land L increases) is essentially the shadow price for land in the absence of additional irrigation, and the second integral is related to the shadow price for the corresponding irrigation.

The shadow price $\partial J(p,w,W_0,L,R,r)/\partial W_0$ for a marginal increase in the initial stock of water on irrigated land can in principle be calculated from (4.34) or (4.46). First consider approach (4.34). The transition equation $\dot{W}_t = R_t - WU_t - \delta W_t$ can be solved for functions $\psi_1(\cdot)$ and $\psi_2(\cdot)$ as follows:

$$\begin{aligned} W(s) &= W(0) + \int_{t=0}^{s} \dot{W}(t)dt = W(0) + \int_{t=0}^{s} R(t)dt - \int_{t=0}^{s} WU(t)dt - \int_{t=0}^{s} \delta W(t)dt \\ &= (1-\delta)^s W_0 + \int_{v=0}^{s} (1-\delta)^{s-v} R(v)dv - \int_{v=0}^{s} (1-\delta)^{s-v} WU(v)dv \end{aligned} \tag{4.51}$$

or (in discrete time)

$$W(s) = (1-\delta)^s W_0 + \sum_{v=0}^{s} (1-\delta)^{s-v} R(v) - \sum_{v=0}^{s} (1-\delta)^{s-v} WU(v) \tag{4.52}$$

$\psi_2(\cdot)$ follows from (4.51) and

$$\dot{W}(s) = R(s) - WU(s) - \delta W(S) \tag{4.53}$$

However the dynamic envelope theorem (4.34) cannot be utilized for the optimal control problem with irrigation (4.49) since neither W nor $\dot{W}$ is specified as an argument in the objective function $\int_{t=0}^{\tau} \{p\, f(x_t, L, WU_t \cdot L) - wx_t\}\, e^{-rt} dt$.

Next consider approach (4.46) to calculation of the shadow price for W_0. The transition equation $\dot{W}_t = R_t - WU_t - \delta W_t$ and (4.46) imply

$$\partial J(p,w,W_0,L,R,r)/\partial W_0 = p\ df(x^*(0),L,WU^*(0)\cdot L)/\partial WU \tag{4.54}$$

It is important to note that the above model allows the contribution of rainfall R_t to the stock of water on irrigated land to vary over the planning horizon. In other words, the firm recognizes that rainfall varies over time and is able to use the irrigation facility to smooth out its water consumption path over time $(WU_0,...,WU_\tau)$, so that water consumption does not vary sharply between periods of high rainfall and drought. This principle benefit of irrigation in a dynamic setting is not included explicitly in a static model. Nevertheless, formulas for calculating the shadow price of the stock of water can be similar in static and dynamic models. Somewhat similar comments apply to the shadow price of irrigated land especially if total irrigated land L does not enter explicitly into the transition equation. Thus the shadow price for the stock of water or irrigated land in a static model may sometimes provide a reasonable approximation to shadow prices in dynamic models.

4.4.2 Shadow Prices Under Certainty When the Transition Equation Is Not Independent of Irrigated Land

Alternatively suppose that the dynamic problem is

$$
\begin{aligned}
J(p,w,W_0,L,R,r) &= \max_{\{(x(t),WU(t))\}} \int_{t=0}^{\tau} \{pf(x_t,L,WU_t \cdot L) - wx_t\}\, e^{-rt}dt \\
s.t. \quad \dot{W}_t &= R_t - WU_t - \delta W_t - h(L) \\
W(0) &= W_0
\end{aligned}
\tag{4.55}
$$

where the transition equation is of type (4.48) depending on L, due to the term h(L) in the transition equation. This transition equation in model (4.55) implies that the shadow price of irrigated land can be calculated as in Caputo's dynamic envelope theorem (4.24):

$$
\begin{aligned}
\partial J(p,w,W_0,L,R,r)/\partial L &= \int_{t=0}^{\tau} p\ \partial f(x^*(t),L,TWU^*(t))/\partial L\ e^{-rt}dt \\
&+ \int_{t=0}^{\tau} p\ \partial f(x^*(t),L,TWU^*(t))/\partial TWU\ \ WU^*(t)\ e^{-rt}dt \\
&+ \int_{t=0}^{\tau} \lambda^*(t)\ \partial h(L)/\partial L\ e^{-rt}dt
\end{aligned}
\tag{4.56}
$$

The last integral on the right hand side of the above equation implies that the calculation of the shadow price of irrigation land is relatively complex and involves terms that have no counterpart in static models. This shadow price can also be specified from (4.44) as follows:

$$\partial J(p,w,W_0,L,R,r)/\partial L = \int_{t=0}^{\tau} p\ \partial f(x^*(t),L,TWU^*(t))/\partial L\ e^{-rt}dt$$

$$+\int_{t=0}^{\tau} p\ \partial f(x^*(t),L,TWU^*(t))/\partial TWU\ WU^*(t)\ e^{-rt}dt \qquad (4.57)$$

$$+\int_{t=0}^{\tau} p\ \partial f(x^*(t),L,WU^*(t)\cdot L)/\partial WU\ \partial\phi(\cdot)/\partial L\ e^{-rt}dt$$

The transition equation $\dot{W}_t=R_t-WU_t-\delta W_t-h(L)$ in (4.55) implies

$$\begin{aligned} WU_t &= \phi(W_t,\dot{W}_t,R_t,L) \\ &= -\delta W_t-\dot{W}_t+R_t-h(L) \end{aligned} \qquad (4.58)$$

so $\partial\phi(\cdot)/\partial L=-\partial h(L)/\partial L$ in (4.57). The shadow price for the initial stock of irrigation water W_0 can be calculated from (4.46) as (4.54), i.e., the general formula for the shadow price $\partial J(\cdot)/\partial W_0$ is influenced by whether irrigation land L enters the transition equation only if L and W_0 interact in the equation $(\partial^2 g(\cdot)/\partial L\partial W_0\neq 0)$.

4.4.3 Shadow Prices Under Risk Aversion and Price Uncertainty

The analysis in the previous section can be extended to a dynamic model with risk aversion and uncertainty, provided that uncertainty is not specific to the transition equation. For example, uncertainty regarding crop output prices is not specific to the transition equation; whereas uncertainty regarding rainfall does influence the transition equation as defined above.

Suppose that the contribution R_t of rainfall in period t to the stock of water available to the firm is known with certainty for all periods t= (0,...,τ), but the crop output price is uncertain. In forming its production plan, the firm assumes that output price p is a random variable distributed independently and with constant mean and variance over time: $p_t = \bar{p} + u_t$ where $Eu_t = 0$, $cov\ u = \sigma_u^2 I$ and in turn $Ep_t = \bar{p}$, $cov\ p = \sigma_u^2 I$. Then the mean and variance of the present value of wealth S from production are defined in terms of the mean and variance of output price p $(Ep = \bar{p},\ V_p = \sigma_u^2)$:

$$
\begin{aligned}
ES &= \int_{t=0}^{\tau} \{Ep\ f(x_t, L, WU_t \cdot L) - wx_t\}\ e^{-rt} dt \\
VS &= \int_{t=0}^{\tau} Vp\ f(x_t, L, WU_t \cdot L)^2\ e^{-2rt} dt
\end{aligned}
\qquad (4.59)
$$

Also assume a linear mean-variance utility function over the mean and variance of the present value of wealth S: U = ES - (α/2) VS.

If the transition equation is independent of total irrigated land L for the firm, then the firm's optimal control problem is

$$
\begin{aligned}
J(Ep, Vp, w, W_0, L, R, r) = \max_{\{(x(t), WU(t))\}} & \int_{t=0}^{\tau} \{Ep\ f(x_t, L, WU_t \cdot L) - wx_t\}\ e^{-rt} dt \\
& -(\alpha/2) \int_{t=0}^{\tau} Vp\ f(x_t, L, WU_t \cdot L)^2\ e^{-2rt} dt \\
s.t. \quad & \dot{W}_t = R_t - WU_t - \delta W_t \\
& W(0) = W_0
\end{aligned}
\qquad (4.60)
$$

Then the dynamic envelope theorem (4.16) implies

$$\partial J(Ep,Vp,w,W_0,L,R,r)/\partial L = \int_{t=0}^{\tau} Ep\ \partial f(x^*(t),L,TWU^*(t))/\partial L\ e^{-rt}dt$$

$$+\int_{t=0}^{\tau} Ep\ \partial f(x^*(t),L,TWU^*(t))/\partial TWU\ \ WU^*(t)\ e^{-rt}dt$$

$$-\alpha\int_{t=0}^{\tau} Vp\ y^*(t)\ \partial f(x^*(t),L,TWU^*(t))/\partial L^*(t)\ e^{-2rt}dt \tag{4.61}$$

$$-\alpha\int_{t=0}^{\tau} Vp\ y^*(t)\ \partial f(x^*(t),L,TWU^*(t))/\partial TWU\ \ WU^*(t)\ e^{-2rt}dt$$

This dynamic shadow price for irrigated land is analogous to the shadow price in the corresponding static model in the same sense that (4.16) is analogous to (4.2), as discussed above.

On the other hand, suppose that the transition equation depends on irrigated land L as in (4.55). Then the term

$$\int_{t=0}^{\tau} \lambda^*(t)\ \partial h(L)/\partial L\ e^{-rt}dt \tag{4.62}$$

must be added to the shadow price as defined in (4.64). Alternatively, (4.44) implies that this shadow price can be defined as

$$\partial J(Ep,Vp,w,W_0,L,R,r)/\partial L = \int_{t=0}^{\tau} Ep\ \partial f(x^*(t),L,TWU^*(t))/\partial L\ e^{-rt}dt$$
$$+\int_{t=0}^{\tau} Ep\ \partial f(x^*(t),L,TWU^*(t))/\partial TWU\ \ WU^*(t)\ e^{-rt}dt$$
$$-\alpha\int_{t=0}^{\tau} Vp\ y^*(t)\ \partial f(x^*(t),L,TWU^*(t))/\partial L\ e^{-2rt}dt$$
$$-\alpha\int_{t=0}^{\tau} Vp\ y^*(t)\ \partial f(x^*(t),L,TWU^*(t))/\partial TWU\ \ WU^*(t)\ e^{-2rt}dt \quad (4.63)$$
$$-\int_{t=0}^{\tau} Ep\ \partial f(x^*(t),L,WU^*(t)\cdot L)/\partial WU \partial h(L)/\partial L\ e^{-rt}dt$$
$$+\alpha\int_{t=0}^{\tau} Vp\ y^*(t)\ \partial f(x^*(t),L,WU^*(t)\cdot L)/\partial WU \partial h(L)/\partial L\ e^{-2rt}dt$$

The shadow price of the initial stock of irrigated water W_0 can be calculated from (4.46) for problem (4.60) as

$$\partial J(Ep,Vp,w,W_0,L,R,r)/\partial W_0 = Ep\ \partial f(x^*(0),L,WU^*(0)\cdot L)/\partial WU$$
$$-\alpha Vp\ y^*(0)\ \partial f(x^*(0),L,WU^*(0)\cdot L)/\partial WU \quad (4.64)$$

This result also holds if the term h(L) is added to the transition equation.

4.4.4 Shadow Prices Under Risk Aversion and Rainfall Uncertainty

More interesting dynamic models of irrigation recognize that rainfall is uncertain and in turn stochastic. In contrast to the previous model where stochastic variables (prices) only appeared as arguments of the objective function, here stochastic variables are arguments of transition equations. As a result the firm cannot choose a deterministic path for all control and state variables (in contrast to the previous model).

This section briefly demonstrates that the general methodology leading to previous dynamic envelope theorems extends to models where variables in transition equations are stochastic. Given the complexity of these stochastic optimal control models an illustration is not provided.

Denote the transition equations as $\dot{x}_t = g(x_t, u_t, t; \beta_t)$ where exogenous variables β are stochastic, and denote the moments characterizing the distribution of β as q_β. Denote a path $\{(x(t), \dot{x}(t), u(t))\}$ as $(X, \dot{X}, U)$. Then the probability of occurrence for a particular path $(X, \dot{X},)$ depends on the deterministic path of controls U, nonstochastic x_0 and moments q_β. Denote the joint probability distribution for $\{(x(t), \dot{x}(t), \beta(t))\}$ as $\theta(X, \dot{X}, \beta | U, x_0, q_\beta)(\theta = 0$ for nonfeasible events). The random variable wealth is defined as $W = \int_{t=0}^{\tau} F(x_t, \dot{x}_t, u_t, t; \beta_t) dt \equiv W(X, \dot{X}, U, \beta)$. Suppose that a risk-neutral firm makes a plan U at time t=0 that maximizes expected wealth:

$$J(q_\beta, x_0) = \max_U EW(U; x_0, q_\beta) \equiv \int_s W(X, \dot{X}, U, \beta)\ \theta(X, \dot{X}, \beta | U, x_0, q_\beta)\ ds \quad (4.65)$$

where $\int_s$ denotes a line integral.

Define the primal-dual

$$G(q_\beta, x_0, U) = J(q_\beta, x_0) - EW(U; x_0, q_\beta) \quad (4.66)$$

If U_A solves (4.65) given $(q_\beta, x_0)_A$, then $G(q_\beta, x_0, U)_A = 0$ and $G(q_\beta, x_0, U_A) \geq 0$ for all (q_β, x_0) (since U_A is feasible for all q_β, x_0). In turn $(q_\beta, x_0)_A >> 0$ implies

$$\partial G(q_\beta, x_0, U)_A / \partial q_\beta = 0 \quad (4.67)$$

$$\partial G(q_\beta,x_0,U)_A/\partial x_0 = 0 \tag{4.68}$$

$$[\partial^2 G(q_\beta,x_0,U)_A/\partial q_\beta \partial x_0] \ \ \textit{symmetric positive semidefinite} \tag{4.69}$$

Then (4.67)-(4.68) imply

$$\partial J(q_\beta,x_0)_A/\partial q_\beta = \partial EW(U;x_0,q_\beta)_A/\partial q_\beta \tag{4.70}$$

$$\partial J(q_\beta,x_0)_A/\partial x_0 = \partial EW(U;x_0,q_\beta)_A/\partial x_0 \tag{4.71}$$

These dynamic envelope theorem results (4.70)-(4.71) indicate that the general primal-dual methodology extends to such stochastic models.

4.5 Specification of Dynamic Duality Models for Econometric Estimation

The above dynamic envelope theorems are important in theoretical analyses (comparative dynamics) and in understanding and modelling shadow prices for capital inputs and resource stocks in dynamic models. Nevertheless these theorems are not appropriate in the specification of dynamic duality models that are intended for estimation. This is because these dynamic envelope theorems are defined in terms of the firm's plans over its entire planning horizon, but in general only the first period plans (t=0) are realized and hence observed. Parameters will generally change over time in contradiction to the firm's expectations, and this will lead the firm to revise its planning problem and hence its plans. Thus empirically observed behaviour over time is presumably a sequence of first period plans defined by a changing sequence of dynamic plans.

As a result, specification of dynamic duality models for econometric estimation is generally based on the Hamilton-Jacobi equation rather than the optimal control problem per se (Epstein). For example, the autonomous optimal control problem (where r is a discount rate constant over the horizon)

$$
\begin{aligned}
J(\beta,r,x_0) &= \max_{\{u(t)\}} \int_{t=0}^{T} F(x(t),\dot{x}(t),u(t),;\beta)\ e^{-rt}dt \\
s.t. \quad \dot{x}(t) &= g(x(t),u(t);\beta) \\
x(0) &= x_0 \quad x(t) \geq 0 \quad \forall\, t
\end{aligned}
\tag{4.72}
$$

implies the following Hamilton-Jacobi equation (at t=0):

$$
r\ J(\beta,r,x_0) = \max_{u}\ F(x_0,g(x_0,u,\beta),u,;\beta) + \partial J(\beta,r,x_0)/\partial x_0\ g(x_0,u,\beta) \tag{4.73}
$$

Thus the empirically observed first period decisions u(0) can be regarded as solving (4.73). Equation (4.73) is not specified explicitly in terms of the firm's generally unobservable planning decisions for periods t>0. Since this is formally a static maximization problem, application of the static envelope theorem to (4.73) yields

$$
\begin{aligned}
r\ \partial J(\beta,r,x_0)/\partial\beta = {} & \partial F(x_0,\dot{x}_0,u_0,;\beta)/\partial\beta + \partial J(\beta,r,x_0)/\partial x_0 \partial\beta\ g(x_0,u_0,\beta) \\
& + \partial J(\beta,r,x_0)/\partial x_0\ \partial g(x_0,u_0,\beta)/\partial\beta
\end{aligned}
\tag{4.74}
$$

For many dynamic problems such as those considered above, the envelope theorem results (4.74) permit the specification of empirically observable first period decisions in terms of derivatives of the optimal value function $J(\beta,r,x_0)$. In this manner duality models can be constructed and estimated for optimal control models.

The above model assumed that the parameters β are static over the planning horizon, but the methodology can easily be generalized to nonstatic parameters (e.g., rainfall R_t, price or variance of price may vary by year) so long as transition equations for β are autonomous. Equations (4.72)-(4.73) are modified as follows (e.g., Epstein and

Denny):

$$J(\beta_0,r,x_0) = \max_{\{u(t)\}} \int_{t=0}^{\tau} F(x(t),\dot{x}(t),u(t),;\beta(t))\ e^{-rt}dt$$

$$\begin{aligned} s.t. \quad \dot{x}(t) &= g(x(t),u(t);\beta(t)) \\ \dot{\beta}(t) &= h(t) \\ x(0) &= x_0 \quad x(t)\geq 0 \quad \forall\ t \\ \beta(0) &= \beta_0 \end{aligned} \tag{4.75}$$

$$\begin{aligned} &r\ J(\beta_0,r,x_0) - \partial J(\beta_0,r,x_0)/\partial\beta\ \ h(t) \\ &= \max_u\ F(x_0,g(x_0,u,\beta_0),u,;\beta_0) + \partial J(\beta_0,r,x_0)/\partial x_0\ \ g(x_0,u,\beta_0) \end{aligned} \tag{4.76}$$

$$\begin{aligned} &r\ \partial J(\beta_0,r,x_0)/\partial\beta - \partial^2 J(\beta_0,r,x_0)/\partial\beta\partial\beta\ \ h(t) \\ &= \partial F(x_0,\dot{x}_0,u_0,;\beta_0)/\partial\beta + \partial^2 J(\beta_0,r,x_0)/\partial x_0\partial\beta\ \ g(x_0,u_0,\beta_0) \\ &+ \partial J(\beta_0,r,x_0)/\partial x_0\ \ \partial g(x_0,u_0,\beta_0)/\partial\beta \end{aligned} \tag{4.77}$$

4.6 Summary

The analysis in this chapter has implications regarding the empirical research in this thesis. Optimal management of irrigation is a dynamic problem, so in principle the shadow price of irrigation water or irrigated land should be estimated from a dynamic model. However, due to data limitations, this is not feasible here. Nevertheless, the results of this chapter indicate that the relation between static and dynamic measures of shadow prices can be quite close.

The familiar first order conditions for the Hamilton-Jacobi equation (4.46) and applications (4.54) and (4.64) indicate how the shadow price of the stock of water to the firm in a dynamic model can be specified in terms of derivatives of the first period objective function and transition equation terms evaluated at the equilibrium levels of first period decision variables. An alternative expression for this shadow price can be derived in terms of derivatives along the optimal path, provided that the state variable or its rate of change is an argument in the objective function (4.34). Thus, in order to calculate the dynamic shadow price of the stock of irrigation water, it is necessary to have estimates of the crop production function with water and the transition equation, along with estimates of the equilibrium levels of first period decision variables. The production function and transition equation can be estimated without directly estimating or solving the dynamic model. If derivatives of the production function and transition equation are relatively insensitive to a reasonable range of estimates for the levels of first period decision variables, then the dynamic shadow price of irrigation water may be reasonably approximated by methods that are essentially static. Moreover if the structure of the transition equation is relatively simple [e.g., as in Equation (4.49) or Equation (4.55)], then empirical research on shadow prices of water can concentrate on the estimation of the production function [see (4.54), (4.64)].

The interpretation of results for the shadow price of irrigated land (incorporating returns to both land and irrigation water) in dynamic models apparently is somewhat more complex. The general results are summarized by (4.24), (4.33) and (4.44) and are illustrated by (4.50), (4.57) and (4.61)-(4.63). Use of a particular unit of irrigation water in crop production for one period is presumed to exclude its use in other periods; whereas it is assumed in this model that a unit of land is used in crop production for all periods with no depreciation or exhaustion related to use. As a result, the shadow price of irrigated land must be defined in terms of derivatives of the production function and perhaps transition equation evaluated at equilibrium levels of decision variables over the entire planning horizon. If total irrigated land does not enter the firm's transition equation for the stock of water per unit of land, then derivatives of the transition equation can be ignored. Thus the shadow price of irrigated land in dynamic models can be approximated given estimates of the crop production function, transition equation and the planned optimal path of decision variables over the planning horizon. If the level of decision variables is assumed to be relatively constant over the planning horizon, then the task of approximating the dynamic shadow price of irrigated land by essentially static methods is somewhat similar to the task of approximating the shadow price of irrigation water by static methods.

Chapter 5. Empirical Models for Farm Level Analysis of the Huai Mae On Irrigation Project

5.1 Introduction

This chapter presents the empirical models used in estimating the impact of irrigation at the selected irrigation site. The chapter begins with a brief discussion of the Huai Mae On irrigation project located in the northern region of Thailand. A statistical survey regarding farming activities of farmers in the study area is presented. The empirical models used in measuring water productivity and evaluating impacts of irrigation at the farm level are formulated. Finally, selected functional forms and estimation procedures are discussed.

5.2 Background Information of the Huai Mae On Irrigation Project

Data for the present farm level analysis were obtained primarily by farm surveys. 103 farmers in the Huai Mae On (HMO) project service areas were interviewed. The farm survey was conducted between June and July 1992 to provide crop production information in the crop year 1991/92: the 1991 wet season production (July-December) and the 1992 dry season production (January-June). Of 103 farmers interviewed, 88 provided sufficient information to be used in the present econometric analysis.

In this section, relevant background information for the HMO irrigation project is presented.

a) Project Profile

Huai Mae On is a tributary of the Mae Kuang river, and part of the Mae Ping Basin, located in Sankampang district, 20 kilometres east of Chiang Mai province in northern

Thailand. Prior to the construction of the storage reservoir, water from the Mae On stream was diverted for irrigating an area of 34,200 rai through the traditional irrigation system. The system originally consisted of 29 temporary wooden weirs, some of which were replaced by more permanent concrete ones. Despite the improvement of the structure, farmers in the area still suffered crop losses due to insufficient water in both the wet and dry growing seasons. This was due to absence of a reservoir to store excess water during the rainy season, and the Mae On stream was too small to service such a large area .

The plan for construction of the HMO reservoir was finally included in the RID's medium scale irrigation package project originated by the government in 1982. The project was partly funded by the Asian Development Bank. The major components of the project were to construct a storage reservoir with outlets for supplying water to an existing irrigation system and to help rehabilitate the existing local irrigation network (i.e., improve the physical weir structure and supervise the existing water user group in irrigation water management).

The project is a zoned earthfill embankment dam which can store water up to a maximum level of 4.53 million cubic metres. However, at least 0.80 million cubic metres must be retained in the reservoir at all times, so the dam provides 3.73 million cubic metres of useful storage. The project was initiated in late 1982, but construction was not started until February, 1985. The reservoir was completed in April 1986 and service began in July 1986. Water in the HMO reservoir is primarily used for agricultural production in both wet and dry seasons. A map of the HMO irrigation project and its service areas[1] is shown in Fig. 5.1.

b) Climatic Conditions

Average annual rainfall in the area is 940 millimetres, which is relatively low in comparison to an average of 1,100-1,400 millimetres for the whole country. Ninety percent of the rainfall occurs in the rainy season (May-October). The area is subjected to frequent droughts during the dry season. Serious drought conditions occur about once in five years, but periods of moisture stress occur every year due to the low rainfall in the area.

c) Service Area

Due to the capacity of the storage reservoir, the project gross area is reduced to only 5,700 rai, with a service area of 5,100 rai. Thus far, only 50 percent of the service area is actually served by the reservoir in the dry season due to insufficient water.

As surveyed and estimated by the RID (1981),[2] there were approximately 530 farm families, with an average family size of 4.8 and average farm size of 10.4 rai. Eighty percent of farms were owner operated and 20 percent of these farmers rented additional land. Average annual per capita income was about 3,750 baht.

There are two main soil types in the HMO service area, i.e., river alluvial soil and andesite derived clays. Both are suitable for paddy rice cultivation as well as other upland crops.

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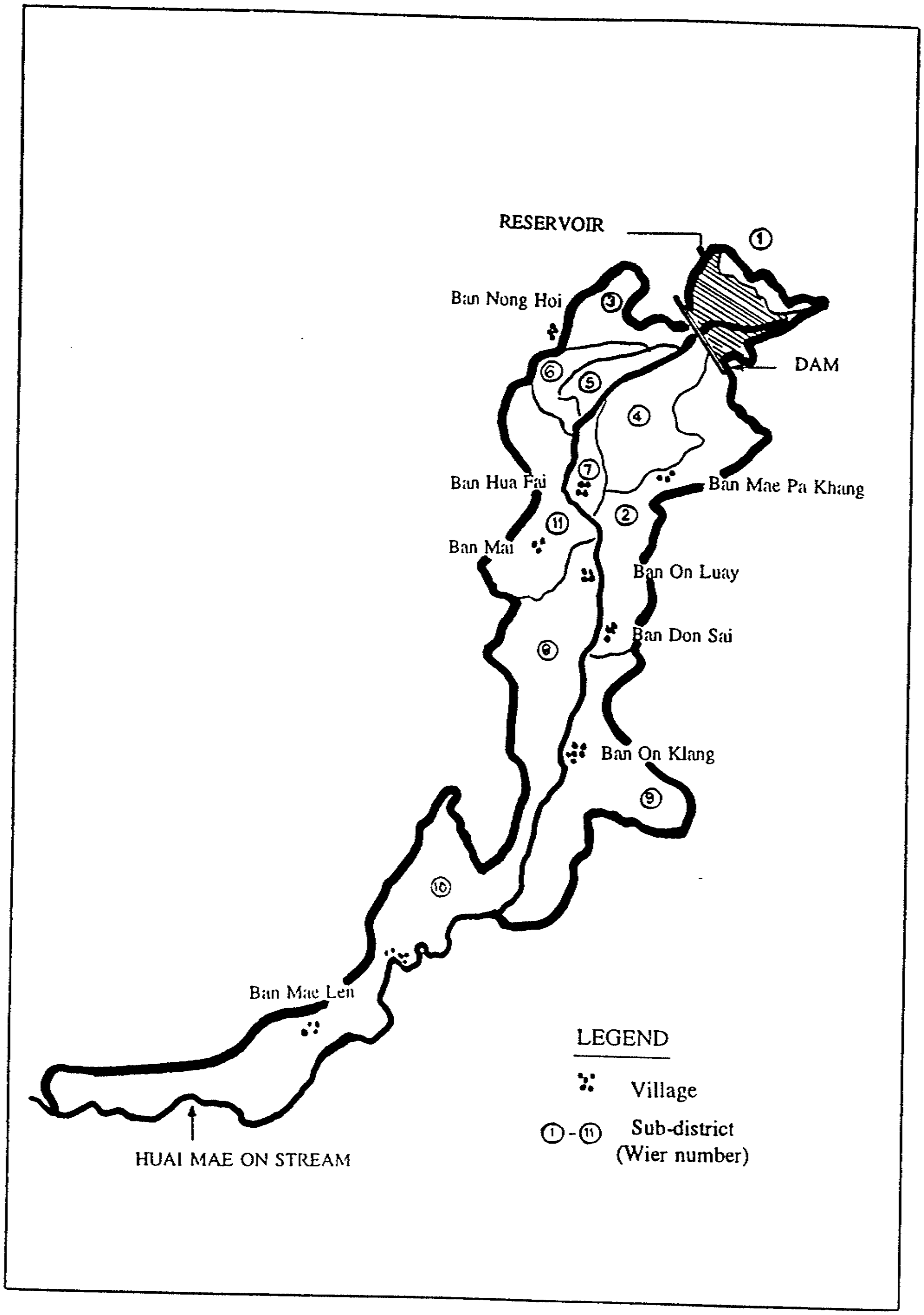
[1] Service areas are the maximum areas intended to obtain irrigation service from the HMO reservoir.

[2] RID Socio-Economic Survey cited in Sir Alexander Gibb & Partners, *Medium Scale Irrigation Package Project*, Feasibility Study, RID, 1981.

Figure 5.1 Map of the Huai Mae On Irrigation Service Areas



Source: Faculty of Social Science, Chiang Mai University, Chiang Mai, Thailand

d) Cropping Pattern

Prior to implementation of the HMO project, rice was the principal crop in the wet season. Groundnuts and tobacco were also grown on lands with insufficient water in the wet season. Glutinous rice, intended primarily for home consumption, accounted for 76 percent of the area in the wet season (July-December). Dry season crops were attempted but led to frequent losses due to insufficient water.

Since completion of the project, a change in cropping pattern and land use has been taken place. The crop intensity, which is defined as the ratio of the wet plus dry season cropping area to the total agricultural area, has increased from 1.12 to approximately 1.50-1.75 (estimates varied by source). The availability of additional dry season water has greatly increased the production of high yielding crops such as garlic, onion and cucumbers. In addition, with the introduction of dairy cattle into the province, farmers have increased high yielding forage crops in conjunction with raising cattle (intended primarily for milk production).

Three distinct cropping seasons have been experienced in the project area. In the wet season (July-December), the typical crops are rice and tobacco. Almost every farmer in the area grows glutinous rice for home consumption in the wet season. Only on areas which are not suitable for rice production do farmers grow alternative crops, usually tobacco and groundnuts. In the dry season (January-June), upland and vegetable crops such as maize, groundnuts, soybeans and cucumbers are preferred because they require less water than paddy rice.

During the dry season, two cropping patterns are generally practiced. First, upland

and vegetable crops are grown from January to March and then land is left fallow for two or three months before the wet season. The second pattern is observed for those farmers in the service areas near the reservoir or head regulator:[3] two dry season crops (normally an upland crop followed by a vegetable crop) can be cultivated (from January to April and from April to June, respectively). Upland crops are not grown in the second half of the dry season since rain may damage crops during harvesting (between May and July).

e) Irrigation Water Management

Water User Group

In the northern part of Thailand, water user groups (WUG) have successfully performed the tasks in irrigation water allocation and management. To date the existence of a strong WUG has been a key factor in effective and successful irrigation schemes. The HMO-WUG played a major role in water allocation even before the dam was built. Following completion of the project, the group has taken control of managing water use and maintenance of the local irrigation system. Assigned tasks in allocating irrigation water are based on experience and accumulated skills. The member's right in using irrigation water is well exercised by customary laws.

After the HMO reservoir was built, the project area was divided into 11 service areas for the purpose of field water management. Each service area has a sub-WUG, and the leaders of each subgroup form the administrative team of the HMO-WUG. The WUG, in cooperation with the project officers, undertake a wide range of management tasks, such as operation and maintenance of secondary canals, settlement of water

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[3] During the dry season, the water stored in the HMO reservoir is usually left at a very low level. Nevertheless, farms located near the reservoir can still pump water for their second dry season crops.

disputes, and control over the distribution of water on an equitable basis. While the WUG takes care of day to day management, distribution and rotation of water at farm level, the HMO project office's main task is to operate at the dam outlet to ensure irrigation water rotation (as requested by the WUG) of stored water for both wet and dry seasons.

Rules of Operation

Irrigation water stored in the HMO reservoir is essentially allocated on a yearly basis. At the end of the wet season (around November to December), the volume of water stored in the reservoir is the main indicator as to what crops should be grown in the subsequent dry season. Given water availability, the project officials roughly estimate crop water requirement based on the amount of stored water and recommend crops to be grown and the area to be irrigated in the dry season. Note that water is usually retained in the reservoir at 1.5-1.6 million cubic metres for wet season rice seedling and land preparation due to typical delays in rainfall at the beginning of the wet season.

Given the water available in the reservoir, fixed area-based allocations (where each individual's share of total water supply is based on his cultivated area) are carried out in the project area. The decisions on water allocation and rotation (both in terms of quantity and time) to each service area have been made entirely by agreement of the group committee. Decisions are usually accepted as being fair. Typically, water share is adjustable and flexible to meet individual requirement as long as shortage and damage do not occur in fields of other members.

Water Charges

In the HMO project area, the WUG has levied an area-based irrigation water fee of 5-20 baht per rai for on-farm management costs. No direct charges have yet been levied on farmers for the purpose of construction cost recovery.

Problems Related to Water Management

Several problems regarding water use and management in the project area were observed during the field survey. First, since water delivery by the RID is based on a rotational system upon farmers' request, conflicts occasionally arise due to insufficient coordination among farmers and between farmers and RID officials. Secondly, ineffective water management can easily arise due to crop diversification and attempts to cultivate more land than can be serviced by available water. Thirdly, a lack of permanent diversion devices for water at farm turnouts has frequently resulted in excessive use of water at farms near the head regulator and shortages at the end of the distribution channels. This is the common 'headender-tailender' problem. Finally, since different crops consume water at different rates and at different times, the practice of allocating water on the basis of acreage together with the practice of a water rotational system can cause problems in water management.

5.3 Statistical Information Regarding Farming Practices in the Sample Data

To provide necessary information on agricultural practices of the farming community in the HMO service areas, relevant data from the 1992 field survey including farm size, land tenure, agricultural land use and crop diversification are presented.

a) Farm Size and Land Tenure

As shown in Table 5.1, 55 of 88 farms were entirely owner-operated, with an average farm size of 5.76 rai. Eleven farmers rented additional land for 1991/92 crop production. Approximately 25 percent of farmers relied entirely on rented land.

Table 5.1 Farm Size and Farm Tenure, Crop Year 1991/92

Type	Number of Farmer	Percentage	Agricultural Land Holdings (rai)	Percentage	Average Farm Size (rai)
Own	55	62.50	316.75	59.74	5.76
Partially Own (own+rent)	11	12.50	107.50	20.27	9.77
Rent	22	25.00	106	19.99	4.81
Total	88	100	530.25	100	6.03

The average farm size for all farmers was 6.03 rai (survey, 1992) compared to 10.4 rai reported for the whole HMO project area (Sir Alexander Gibb & Partner, 1981). This farm size is small in comparison to an average of 22.3 rai for the North and 26.4 rai for the nation in 1983 (Phantumvanit, 1987).

As shown in Table 5.2, the amount of land rented for 1991/92 crop production ranged from 2 to 9 rai with an average of 4.7 rai per farm. In the survey area, land rents were paid as either cash or a share of total crop. The tenants normally paid between 25 to 50 percent of total crop output. The maximum rental share of 50 percent usually occurred when the landlord bore the cost of all variable inputs.

Table 5.2 **Rented Land, Crop Year 1991/92**

Category	Number of Farmer	Percentage	Area (rai)	Percentage	Average Area (rai)	Minimum Area (rai)	Maximum Area (rai)
Cash Rent	8	24.24	31.5	20.26	3.94	2	6
Rent (baht/rai)	-	-	-	-	391.27	50	2,000
Payment in Kind	23	69.70	115	73.95	5	2	9
Rent in Paddy Rice Equivalence (tang/rai)	-	-	-	-	23.30	10	55
Rent Payment (payment not identify)	1	3.03	2	1.29	2	-	-
Free Rent (rent is waived from relatives)	1		7	4.50	7	-	-
Total Land Rented	33	100	155.5	100	4.71	2	9

Approximately 25 percent of farmers who rented land (with 20 percent of the total rented acreage) paid rent in cash, with an average of 391 baht per rai. Based on the average figure, tenants may be better off paying cash rent. Given the output prices for the 1991/92 crop year, cash rent was only half of the sharecropped rent.

b) Agricultural Land Intensity

As shown in Table 5.3, most agricultural land was used for cultivation in the wet season of 1991/92 crop year, with the cultivated land varying from 1.5 to 15 rai per farm. In the dry season, 42 percent of the total surveyed area was cultivated. The remaining areas were left idle due to either insufficient water or higher wages from off-farm employment.

Table 5.3 Agricultural Land Intensity, Crop Year 1991/92

Cropping Season	Number of Farmer	Cultivated Land (rai)	Ratio of Cultivated Land to Total Land	Minimum Area (rai)	Maximum area (rai)
Wet	88	512.75[a]	0.97	1.50	15
Dry	66	222.75	0.42	0.25	10
Wet+Dry	88	739.50	1.39	1.50	15

[a] The rest of total agricultural land (17.5) rai was leased.

Agricultural land use intensity (defined as the ratio of cultivated land in both wet and dry seasons to total agricultural land) in the survey area during the 1991/92 crop year averaged 1.4.

c) Crop Diversification

In the wet season 1991/92, approximately 90 percent of the surveyed agricultural land was planted to rice, and the remaining 10 percent was planted to groundnuts (Table 5.4).

Table 5.4 Crop Diversification, Crop Year, 1991/92

Crop/ Growing Season	Number of Farmer	Total Planting Area (rai)	Percentage of Total Cultivated Land in Each Season	Average Planting Area (rai)	Minimum Area (rai)	Maximum Area (rai)
a) Wet season						
Glutinous Rice	83	431.75	84.20	5.2	1.5	13
Non-glutinous Rice	3	30	5.85	10	4	14
Tobacco	9	51	9.95	5.67	2	15
Total	95	512.75	100	-	-	-
b) Dry Season						
Tobacco	32	75.5	33.89	2.36	0.25	4
Maize	7	18	8.08	2.57	1	6
Cucumber	8	14.5	6.51	1.81	0.5	4
Garlic	24	46.3	20.79	1.93	0.25	6
Shallot	7	15.5	6.96	2.21	0.75	4
Grass	3	6	2.69	2	1	4
Groundnuts	5	11.75	5.27	2.35	2	3
Soybeans	6	34.25	15.38	5.71	4.75	8
Pepper	1	1	0.45	1	1	1
Total	93	222.75	100	-	-	-

Allocation of agricultural land was more diversified in the dry season. The main dry season crop was tobacco, accounting for almost 34 percent of total surveyed dry season cultivated area. Other significant crops include garlic, shallot, groundnuts, soybeans, and cucumbers. From the surveyed samples, these crops together with tobacco, accounted for almost 90 percent of the dry season planting area.

5.4 The Empirical Model

The marginal value of irrigation is approximated from estimates of a production function. The dual approach is not employed in the farm level analysis because there is no (or relatively small) variation in input and output prices across farms in the cross-section data.[4]

From the survey, the application of irrigation water for each specific crop among farmers in the HMO project area appeared to be rather homogeneous in terms of the quantity of water applied and the timing of application. This was likely the result of the practice of the rotational fixed area-based water allocation exercised in the study area (as previously noted). In addition farmers in the area may have similar experience and skills in irrigation. Moreover, data on the exact amount of irrigation water applied to each crop could not be obtained in the interviews. As a consequence, the amount of irrigated land is used as a proxy variable in indirectly investigating the productivity of irrigation water at the farm level.

5.4.1 Production Model Specification: Wet Season

In the wet season, the productivity of irrigation water will be derived primarily from rice production as it is grown on approximately 90 percent of the total crop land. However, since average rainfall in the HMO irrigation project area (Sankampang district) is

[4] Mean and standard deviation of input and output prices of the major crops obtained from farm survey data are summarized in Appendix A.

relatively low, supplemental water from either surface irrigation water or groundwater is necessary for growing rice even in the wet season. Rainfed areas and areas with insufficient irrigation water are used to grow other upland crops which require less water.

Since most irrigated land is planted to rice and rice is not cultivated in the absence of irrigation, it is not appropriate to measure the difference between the productivities of irrigated and non-irrigated land in producing wet season rice. Alternatively, the productivity of irrigation water in the wet season at the farm level will be approximated as the difference between the productivity of irrigated land (as estimated from the production model) and the wet season rent on non-irrigated land nearby. In other words, land rent on rainfed area under similar climatic conditions and agricultural practices will be used to proxy the productivity of non-irrigated land in the calculations.

The wet season rice production model can be specified as

$$Y_R = f(A,Tr,F,S,L,Hi,DUM...H,DUM...O) \quad (5.1)$$

where Y_R denotes wet season rice production, and A represents the irrigated area planted with rice. The number of tractor hours and chemical fertilizer used in wet season rice production are denoted by Tr and F, respectively. S denotes quantity of rice seed. A dummy variable for seed quality (DUM_H) is also constructed such that it equals one when rice is planted with high yielding varieties (HYVs) and equals zero otherwise. This is to capture the impacts of modern and traditional rice varieties on rice production in the survey area.[5] Hi denotes expense on herbicide and insecticide inputs. L represents labour input which is classified by type of labour and labour activities. In this study, types of labour include own (Lo), hired (Lh), and exchanged labour (Le). Labour activities in rice production include land preparation (L1), planting (L2), fertilizer application which also includes herbiciding and insecticiding (L3), and finally harvesting (L4). However, none of these categories are differentiated by sex.

In the present analysis, expenditure data is used in place of quantity data for several groups of inputs (such as insecticides and herbicides) in the estimation of production models. Use of expenditure data as a proxy for input levels in the production function will generally lead to biased estimates if input price variations are substantial, but the method is justified in the present study. Expenditure data can be integrated as an input quantity index if variation in prices is relatively small in the data set, as in this study. Variations in prices for insecticides and for herbicides reflects differences in quality for the inputs rather than differences in prices for a homogeneous input. In this case, expenditure data provides an input quantity index adjusted for differences in quality of inputs. Aggregation of inputs into several input quantity indexes is necessary in order to reduce multicollinearity problems in estimation of a production function.

In addition to quantitative inputs, land ownership is also hypothesized to have a significant influence on rice production through the levels of farm management and investment (Debertin, 1986). In other words, security of land tenure may encourage a

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[5] About 46 percent of the 1991 wet season rice area was planted with HYVs. Apparently, there was no significant difference in seed prices between traditional and high yielding rice varieties. The choices of seed variety seemed to have been partly influenced by quality preferences.

farmer to invest or manage his land so as to maintain or increase soil fertility. Moreover, land ownership also enables the farmer to use his land as collateral to secure credit for the purchase of inputs. As in the case of seed quality, differences in land ownership is proxied by a dummy variable. The dummy variable (DUM_O) equals one if the farmer owns all of the land that he cultivates for rice and equals zero otherwise. Land quality is treated as constant in the present farm level analysis since there is no evidence regarding a difference in soil fertility between the two major soil types in the survey area.

5.4.2 Production Model Specification: Dry Season

As previously shown in Table 5.4, agricultural production was more diversified in the dry season than in the wet season. Nine crops were planted in the survey area in the 1992 dry season. Tobacco and garlic were grown on more than 50 percent of the total dry season area by 32 and 24 farmers, respectively. However, adequate data could not be obtained for tobacco production.[6] Estimation of the productivity of irrigation water for the remaining crops (shallot, groundnuts, soybeans and cucumbers were selected based on data quality) will employ an implicit production function or transformation function.[7]

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[6] This is due to the fact that tobacco farms in the survey area were dominated by contract farming system. Thirty out of 32 tobacco farmers interviewed received credit in terms of necessary variable inputs including land preparation services from the Thai Tobacco Monopoly, several private tobacco companies located in the area and also the large farmers who operate their own curing barns from the area nearby. Since accurate responses on the quantities of inputs used could not be obtained from interviews, the estimation of the tobacco production is precluded form the present analysis.

[7] It should be noted that data and information on production of different crops were collected assuming disjoint technology and allocable inputs. A transformation function relating levels of m outputs and n inputs can be expressed as

$$F(Y_1,\ldots,Y_m,X_1,\ldots,X_n) = 0 \tag{5.2}$$

Assuming disjoint technology, the transformation function in (5.2) can be reduced to crop-specific production functions

Model specifications for production functions of garlic and other dry season crops in the survey area are briefly presented as follows.

a) Garlic

Garlic was grown by 24 farms on approximately 20 percent of the total dry season area (Table 5.4). The initial model for garlic production is

$$Y_G = f(A,F,S,L,Hi,DUM...O) \tag{5.4}$$

where Y_G represents garlic production, L represents input labour which is again assumed to be heterogenous in terms of type of labour and labour activity. Type of labour are own and hired labour. Note that exchange of labour is not commonly practiced for dry season crops because the planting areas are relatively small and most farmers also work off-farm. Labour activities along with other variables in (5.4) are defined similarly to the wet season rice model. Seed quality is not included because garlic seed used in the area is homogeneous in quality. A dummy variable for land ownership is again included to capture differences in managerial ability between those who own and rent land.

Only three out of 24 garlic farms grew garlic in combination with another crop. For almost all garlic farms, any potential jointness in technology between garlic and other crops may be ignored in the empirical model.

b) Other Crops

Since each of the remaining seven crops was grown by relatively few farmers (as

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$$Y_j = f^j(X_{1j},...,X_{nj}) \quad j=1,...,m \tag{5.3}$$

In other words, the detailed information on input-output relationship were collected specifically for every crops produced in the 1991/92 crop year.

previously shown in Table 5.4), disjoint production functions could not be estimated for each specific crop. Instead a multi-output transformation function was considered. Based on data quality, four crops (shallot, groundnuts, soybeans, and cucumbers) were selected. The transformation function (5.2) can be inverted to obtain (assuming $(\partial F(\cdot)/\partial X_1 \neq 0)$

$$X_1 = h(Y_1,...,Y_m,X_2,...,X_n) \qquad (5.5)$$

where X_1 represents the factor of production whose productivity is of particular interest. For this study, (5.5) is expressed as

$$A = h(Y_1,Y_2,Y_3,Y_4,F,L,Hi) \qquad (5.6)$$

where A represents the sum of irrigated areas planted to four crops (shallot, groundnuts, soybeans and cucumbers) and outputs of those four crops are denoted by Y_1, Y_2, Y_3, and Y_4, respectively. Other variable inputs used in producing these crops, i.e., F, L, and Hi are defined as before.

5.4.3 Functional Form

It is well known that second order flexible functional forms such as the Translog or Quadratic are less restrictive than Cobb-Douglas or Linear production functions. The Translog and Quadratic provide a second order differential approximation to a true unknown production function, whereas the Cobb-Douglas and Linear provide only a first order differential approximation (e.g., Chambers). However, multicollinearity problems often lead to difficulties in direct estimation of second order flexible functional forms for production functions.

In dealing with cross-section farm survey data with several physical inputs and dummy variables specified in the initial production models, the Cobb-Douglas and the translog functional forms do not normally represent appropriate choices simply because the log of zero value is undefined. Alternatively, all the models proposed in this farm level analysis section are estimated assuming linear and semi-logarithmic functional forms.

As a result, this study primarily estimates first order differential approximations to production functions. The following linear and semi-logarithmic functional forms are emphasized for single output production functions:

$$Y = \alpha_0 + \sum_{i=1}^{n} \alpha_i X_i \tag{5.7}$$

$$\ln Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i \tag{5.8}$$

A log-linear (Cobb-Douglas) form is not considered because input levels are occasionally equal to zero. Similarly a linear functional form is adapted for the inverted transformation function (5.5) because some output levels ($Y_1,...,Y_4$) are generally equal to zero.

5.4.4 Estimation Procedure

The models to be estimated in the present farm level analysis consist of wet season rice production, dry season garlic production, and an inverted transformation function for the four dry season outputs (shallot, groundnuts, soybeans, and cucumbers).

In general many inputs are endogenous to the models, although various capital inputs may be approximated as predetermined. Moreover, choices of inputs are presumably influenced by variables such as managerial ability that are omitted from the model. As a result, input levels are likely to covary with the disturbance term in the specified production function. This implies that the ordinary least squares (OLS) estimators of the production function are likely to be biased and inconsistent.[8] The inverted transformation (5.6) includes output levels as explanatory variables, and these output levels are inevitably correlated with the disturbance in the model specification. Thus OLS estimation presumably is least appropriate for the inverted transformation function.

Nevertheless, it is not clear that instrumental variable methods of estimation such as the two-stage least squares (2SLS) are superior to OLS for this study. The asymptotic properties of 2SLS may not be well approximated for a relatively small number of observations as in this study. Moreover, the choice of instrumental variables is limited for this study, primarily because input and output prices do not vary over the data set. There can be difficulties in finding sufficient instruments in the data set to achieve identification. In any case, the relatively small number of important instruments collected in the data set implies a substantial loss in asymptotic efficiency for 2SLS relative to 2SLS using all important instruments.

A further problem is that endogenous output levels appearing as explanatory

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[8] The omission of relevant explanatory variables generally leads to biasedness and inconsistency of the least squares estimator unless those omitted variables are not correlated with the variables included in the model or they do not have significant impacts on the dependent variable. However, neither is likely to be the case in the present analysis.

variables in the inverted transformation function (5.5) are often equal to zero, i.e., the distribution of these variables is truncated at zero. In general such truncations of dependent variables imply that least squares techniques are not optimal. Instead this limited dependent variable model can be expressed as a Tobit model and estimated by maximum likelihood. Estimation of a model with a single dependent variable is relatively straightforward (e.g., Chow, 1983), but the above model (5.5) involves multiple limited dependent variables.

5.5 Summary

The Huai Mae On irrigation project has been chosen as the focus for the present farm level analysis. Two single crop production function models (for wet season rice production and dry season garlic production) and an inverted transformation function for dry season multiple outputs (shallot, groundnuts, soybeans, and cucumbers) are formulated. There are serious difficulties in econometric estimation of all models. Given data limitations it is not clear that 2SLS is more appropriate than OLS, so all models will be estimated by OLS and (to the extent that identification can be achieved) 2SLS.

Chapter 6. Empirical Models for National Level Analysis

6.1 Introduction

This chapter presents empirical models used in estimating the productivity of irrigation water from national level data. Both primal and dual specifications of technology are considered. The analysis is subdivided into wet and dry growing seasons and is limited to rice, which is the most important crop in the Thai economy. Functional forms and estimation procedures are discussed.

6.2 Primal Analysis

As in the analysis of farm level data, the primal production approach is employed to estimate the productivity and impacts of irrigation from national data. Since rainfall in the wet season is almost sufficient for most crops other than rice, the benefits of irrigation in the wet season are limited primarily to rice production.[1] In the dry season, Thai irrigated agriculture is more diversified. Several upland crops and vegetables are widely grown especially in the North where climatic conditions are favourable. However, adequate time series data on production (i.e., quantities of inputs and outputs) is available only for rice. Thus the national level analysis for both wet and dry growing seasons will be limited to rice production.[2]

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[1] This is also supported by the fact that rice accounts for almost 90 percent of the total wet season irrigated area (see Chapter 2).

[2] In the dry season, rice still accounts for approximately 60 percent of the total dry season irrigated area.

6.2.1 Wet Season Rice Production

6.2.1.1 Model Specification

Since national level data on irrigation water consumption in agriculture or rice production is not available, the productivity of irrigation water will be proxied by the difference in productivities for irrigated and non-irrigated land in rice production. As emphasized earlier, these approximations are biased upward if the quality of irrigated land is higher than the quality of non-irrigated land.

Separate production functions may be specified for production of rice on irrigated and non-irrigated land:

model I

$$Y_{Ia} = f^1(Ia, X_{Ia}) \qquad (6.1)$$

$$Y_{Na} = f^2(Na, X_{Na}) \qquad (6.2)$$

Here Y_{Ia} and Y_{Na} denote annual wet season rice production on irrigated and non-irrigated lands, respectively. Ia and Na represent wet season irrigated and non-irrigated areas planted to rice. X_{Ia} and X_{Na} are vectors of other input levels for irrigated and non-irrigated rice production, respectively.

The difference between marginal physical products for land in these two models, i.e., $\partial f^1(Ia,X_{Ia})/\partial Ia - \partial f^2(Na,X_{Na})/\partial Na$, is attributed by assumption to irrigation. This assumes that irrigated and non-irrigated land are of equal soil quality.

Alternatively the following specification of technology can be adopted:

model II

$$Y = g(Ia,Na,X) \qquad (6.3)$$

Here Y represents total rice production in the wet season and X represents total input use (other than land) in the wet season, i.e., $Y=Y_{Ia}+Y_{Na}$ and $X=X_{Ia}+X_{Na}$. Model I imposes the restriction that technologies for rice production on irrigated and non-irrigated land are disjoint, whereas model II allows for the possibility of joint production. If production is disjoint (as may be reasonable), then model I is superior to model II in the sense that it incorporates more information (the allocation of Y and X to irrigated and non-irrigated rice production). On the other hand, model II is invariant to errors in measurement regarding this addition information (data is more readily available regarding X than its allocation X_{Ia}, X_{Na}. The productivity of irrigation water can be observed from the difference between the productivity of irrigated and non-irrigated land essentially as in model I.

The third empirical formulation for the primal wet season rice production model that will be used in this analysis is

model III

$$Y = h(Ia,Ta,X) \qquad (6.4)$$

where Ta represents total wet season rice area, i.e., Ta=Ia+Na. This is identical to model II except that Na is replaced by Ta in model III. This model specification provides the simplest test of differences in productivity between irrigated and non-irrigated land: if there is no difference in productivity, then $\partial h(Ia,Ta,X)/\partial Ia=0$.

Relevant independent variables (X) that are initially included in the models are amount of rainfall (R), fertilizer (F), number of tractors (Tr), labour (L), and technology (T). In investigating the productivity of irrigation water using the primal approach, the initial specifications of rice production function for the wet season are as follows (omitting subscripts for X_{Ia} and X_{Na}):

model I

$$Y_{Ia} = f(Ia,R,F,Tr,L,T) \tag{6.5}$$

$$Y_{Na} = f(Na,R,F,Tr,L,T) \tag{6.6}$$

model II

$$Y = f(Ia,Na,R,F,Tr,L,T) \tag{6.7}$$

model III

$$Y = f(Ia,Ta,R,F,Tr,L,T) \tag{6.8}$$

Equations (6.5) and (6.6) are the general representation of model 1, and (6.7) and (6.8) refer to model 2 and 3 as discussed previously. The selection of these variables can be rationalized as follows.

Amount of rainfall (R)

The main sources of water used in wet season rice production are rainfall and irrigation water. In the wet season, irrigation water is usually used to supplement rainfall mainly when the rain is delayed or inadequate for optimal growing conditions. This generally occurs during the first half of the growing period when the amount and distribution of rainfall can be unpredictable. The amount of rainfall is included in the models to isolate the impact of irrigation water in the production process. Two variables are employed to proxy rainfall conditions in this analysis. These include average annual rainfall during the wet season rice growing period which is normally a 6-month period from July to December (WRM) and average annual effective rainfall[3] during the rice growing period (WERM).

Fertilizer (F)

Fertilizer is the most commonly used modern inputs in Thai agriculture. Fertilizer imports have increased almost tenfold during the past two decades and about threefold during the past decade.[4] Fertilizer use in both wet and dry season rice production accounts for approximately 44% of all fertilizer use annually. During the study period, from 1969/70 to 1990/91, application of fertilizer (the combination of ammonium sulphate, urea, 16-20-0, and 16-16-8) to wet season rice production remained stable, at a relatively low average of 5-7 kilogram per rai. This is probably due to low nitrogen

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[3] The method in calculating the amount of effective rainfall employed in this study is taken from Boonyatarokul, 1983. Percentage of effective rainfall is calculated as follows.

Average monthly rainfall -millimetre	Effective rainfall-millimetre (%)	
200	200	(100)
250	237.5	(95)
300	270	(90)
350	292.5	(83.6)
400	310	(77.5)
450	320	(71.1)
500	325	(65)

[4] During the period 1968-73 production of nitrogen based fertilizer was protected by giving the domestic producer a monopoly on fertilizer imports. The relatively high price of fertilizer to agricultural outputs limited fertilizer use in Thai agriculture during that period. In order to encourage farmers to use more fertilizer, the government began a fertilizer distribution program in 1975, selling fertilizer at reduced prices. However, the market share of the government-supported fertilizer has been only 6 to 7 percent of the total fertilizer use annually, so its impact on fertilizer prices has been minimal.

response for traditional or improved traditional varieties which are usually grown in the wet season, combined with a generally high fertilizer-rice price ratio. In contrast, high yielding rice varieties, which are generally grown in the dry season, require better water control and more fertilizer. Fertilizer use in dry season rice production ranged between 40 to 70 kilogram per rai from 1975 to 1990. Due to the relatively low fertilizer application rate in rice production, fertilizer may significantly constrain rice production in Thailand.

Tractor (Tr)

Levels of capital equipment in Thai agriculture have increased since agriculture became more commercialized in the early 1970s. Use of tractors has increased in spite of the relatively small-scale of farm operations. Farmers have purchased tractors for their own farm activities and also for rental to other farmers. Tractors are especially important to farmers during periods of land preparation when timing is crucial.

In the present macro analysis, tractors is included in initial models as a proxy for capital equipment in rice production. Given data limitations, this is measured as the number of tractors employed in agriculture. This approximation is reasonable only to the extent that there is no significant variation in average work hours per tractor or in average quality of tractors over time.

Labour (L)

Agricultural production in Thailand is still characterized by small- to medium-scale farm operations which are labour intensive especially during the peak planting and harvesting periods. Unfortunately, aggregate time series data on labour utilization in rice production is not available, and information on the distribution of labour in major rice production activities also is not available. Instead data is available on total labour participation in the agricultural sector, i.e., the total labour force from 15-64 years of age engaged in all agricultural occupations.

Since this data appears to provide only a crude approximation to labour hours employed in rice production, an alternative data set for the labour variable is created from available data on the annual average cost of labour in wet season rice production. The quantity of labour used (man-days) in producing rice is computed by dividing total labour cost by the agricultural wage rate (as proxied by the official minimum wage rate for non-skilled labour).

Technology (T)

There has been considerable evidence of a modest technological revolution in Thai rice cultivation. High yielding varieties, i.e., the RD (Rice Department) varieties were first introduced in 1969. Adoption of these varieties has been accompanied by increased use of subsidized fertilizer, improved farming techniques. A greater emphasis has been placed on government extension services.

In an attempt to proxy the change in rice production techniques that has occurred over time, a moving average rice yield for the three previous years and a simple time trend, are considered. Of course both of these variables may be correlated with many omitted variables in addition to technical change.

Details on the definition and measurement of variables, sources of data and all time series data used in estimating the wet season primal models are given in Appendix

B and C.

6.2.1.2 Functional Form

Much of the discussion on functional forms for production functions (section 5.4.3) extends to time series data. Second order differential approximations to a production function, such as a Translog, are less restrictive than first order approximations, such as a Cobb-Douglas. Nevertheless, direct estimation of a Translog function is often difficult due to high multicollinearity, in contrast to a Cobb-Douglas. Multicollinearity problems can be reduced substantially if standard first order conditions for static competitive profit maximization (marginal value product equals input price) are estimated jointly with the Translog equation (imposing all cross-equation restrictions), but these first order conditions will lead to inconsistent estimators of the production function unless firms are risk-neutral. Since most farmers presumably are risk-averse, estimation of these first order conditions may not be appropriate.

Three functional forms for production are considered. The most restrictive and most parsimonious form is the Cobb-Douglas:

$$Y = \alpha_0 \mathop{\pi}_{j=1}^{n} X_i^{\alpha_i} X_j^{\alpha_j} \qquad (6.9)$$

or in logarithmic form as:

$$\ln Y = \ln\alpha_0 + \sum_{j=1}^{n} \alpha_j \ln X_j \qquad (6.10)$$

where Y denotes annual wet season rice production. Variable inputs (X) include rice planting area, fertilizer, amount of rainfall, number of tractors, labour, and technology.

The following Translog and Quadratic forms are also considered:

$$lnY = \ln\beta_0 + \sum_{i=1}^{n} \beta_i \ln X_i + 1/2 \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} \ln X_i \ln X_j \tag{6.11}$$

$$Y = \delta_0 + \sum_{i=1}^{n} \delta_i X_i + 1/2 \sum_{i=1}^{n} \sum_{j=1}^{n} \delta_{ij} X_i X_j \tag{6.12}$$

Due to high multicollinearity, the general Translog and Quadratic functional forms (6.11)-(6.12) are not emphasized here. Instead restricted versions of these functions are considered, where all off-diagonal terms or cross effects in (6.11)-(6.12) are restricted to equal zero ($\beta_{ij}=0$ and $\delta_{ij}=0$ for all $i \neq j$). The resulting models are intermediate between the first and second order flexible forms in terms of restrictiveness and multicollinearity.

6.2.1.3 Estimation Procedure

As in the farm level analysis, the proposed macro models ((6.5)-(6.9)) will be estimated by OLS and 2SLS. In contrast to the analysis of farm level data, instrumental variables employed in 2SLS estimation include prices: fertilizer price, the agricultural wage rate as proxied by official minimum wage rate for non-skilled labour, lagged farm price for rice and lagged prices of alternative wet season crops i.e., maize, groundnuts, soybeans, and mungbeans. Irrigated and non-irrigated rice areas, total rice area and number of tractors are treated as quasi-fixed inputs in the estimation process. Laspeyres and Tornqvist index formulas are employed to aggregate several input variables which are not of major concern. These indexes are presented in Appendix D.

6.2.2 Dry Season Rice Production

For the wet season, the productivity of irrigated and non-irrigated land in rice is compared. In contrast, in the dry season rice can be produced on irrigated land because rainfall is not sufficient for production of rice[5] (Smitthmadhindra, 1991). Thus the marginal productivity of irrigated land in dry season rice production can be attributed entirely to irrigation.

The dry season rice production function can be specified similarly to the wet season. The only difference is that dry season non-irrigated rice acreage can be ignored. In the absence of irrigation, agricultural land in the dry season is usually left idle. Thus the opportunity cost of non-irrigated agricultural land is typically zero or approaches zero (at least in the short-run when non-irrigated land is not allocated to other uses).

The initial empirical dry season rice production model is formulated as follows:

$$Y_d = f(Ia_d, DRM, F_d, Tr, L_d, T) \qquad (6.13)$$

where Y_d is dry season rice production, Ia_d is rice acreage (under irrigation). Rainfall conditions are also included in the model in an attempt to separate the impact of water attributable to irrigation and rainfall. Rainfall (DRM) is defined as average rainfall during the dry season rice growing period (January to June). F_d denotes the level of chemical fertilizer used in dry season rice production. L_d represents labour (man-days) employed in dry season rice production, and is computed as in the wet season rice model. Tr and T are defined as in the wet season models.

Functional forms and estimation procedures employed in the dry season rice model are similar to those employed in wet season rice production. Details on the definition of

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[5] Similar information was also obtained from personal communications with government officials in the Irrigated Agriculture Branch, RID, and Department of Agricultural Extension, MOAC.

variables, variable measurement, data sources, and all time series data used in estimating the dry season primal model are presented in Appendix B and C.

6.3 Dual Analysis

An alternative dual approach to estimation of productivity and impacts of irrigation is also conducted, using national time series data. The dual models are formulated for both wet and dry season rice production. The time series data used in the wet and dry season dual analysis are from 1973 to 1990 and from 1975 to 1990, respectively.

6.3.1 Wet Season Rice Production

6.3.1.1 Model Specification

In the dual analysis, the supply of rice and related factor demands are assumed to depend upon prices of rice, fertilizer and labour. Other explanatory variables in the supply equation include weather and number of tractors (as a proxy for capital). Assuming rice production is disjoint from other agricultural technologies, the input demands and output supply equation conditional on rice acreage are independent of prices and acreage of other crops. This separability assumption can also be justified because most paddy land planted to wet season rice is not suitable for other crops due to minimal water control.

The initial specification for the system of input-output estimating equations is

$$F = f(W_1, W_2, P, Ia, Ta, R, T, Tr) \qquad (6.14)$$

$$L = f(W_1, W_2, P, Ia, Ta, R, T, Tr) \qquad (6.15)$$

$$Y = f(W_1, W_2, P, Ia, Ta, R, T, Tr) \qquad (6.16)$$

where F and L denote fertilizer and labour employed in wet season rice production, and

W_1 and W_2 are prices of fertilizer and labour, respectively. Total wet season rice output is denoted by Y and Tr is the number of tractors. Details on units of measurement are given in Appendix B.

Expected price for rice (P) is modelled alternatively as a one-year lag on farm prices and a 3-year moving average of farm prices. The quantity of labour (L) is measured as in the primal model. Weather is proxied by rainfall (R) as in the primal model. Technology (T) is also proxied as in the primal model. In (6.14)-(6.16), annual irrigated rice acreage and total rice acreage are denoted by Ia and Ta, respectively.

6.3.1.2 Functional Form

Equations (6.14)-(6.16) are modelled assuming two different flexible forms for profit functions: a Normalized Quadratic and a Generalized Leontief.[6] Equations (6.14)-(6.16) are then specified by Hotelling's lemma.

a) The Normalized Quadratic Profit Function

A Normalized Quadratic profit function can be postulated as:

[6] A Translog profit function is not modelled because data on profits in rice production is not available.

$$
\begin{aligned}
\pi/W_2 = {} & \alpha_0+\alpha_1(W_1/W_2)+\alpha_2(P/W_2)+\alpha_3 Ia+\alpha_4 Ta \\
& +\alpha_5 R+\alpha_6 T+\alpha_7 Tr+\beta_1(W_1/W_2)(P/W_2) \\
& +\beta_2(W_1/W_2)(Ia)+\beta_3(W_1/W_2)(Ta) \\
& +\beta_4(W_1/W_2)(R)+\beta_5(W_1/W_2)(T) \\
& +\beta_6(W_1/W_2)(Tr)+\beta_7(P/W2)(Ia) \\
& +\beta_8(P/W2)(Ta)+\beta_9(P/W2)(R) \\
& +\beta_{10}(P/W2)(T)+\beta_{11}(P/W2)(Tr) \\
& +\beta_{12}(Ia)(Ta)+\beta_{13}(Ia)(R)+\beta_{14}(Ia)(T) \\
& +\beta_{15}(Ia)(Tr)+\beta_{16}(Ta)(R)+\beta_{17}(Ta)(T) \\
& +\beta_{18}(Ta)(Tr)+\beta_{19}(R)(T)+\beta_{20}(R)(Tr) \\
& +\beta_{21}(Tr)(T)+\delta_1(W_1/W_2)^2+\delta_2(P/W_2)^2 \\
& +\delta_3(Ia)^2+\delta_4(Ta)^2+\delta_5(R)^2+\delta_6(T)^2+\delta_7(Tr)^2
\end{aligned} \tag{6.17}
$$

where π is variable profit (revenues minus variable costs), and all independent variables are specified as in the previous section. Linear homogeneity in prices for the profit function is imposed through normalization (i.e., dividing profit and prices by labour input price W_2). Then Hotelling's lemma implies fertilizer demand and rice supply equations.

$$
\begin{aligned}
F = {} & -(A_1+A_{11}(W_1/W_2)+A_{13}(P/W_2)+B_{11}Ia \\
& +B_{12}Ta+C_{11}R+C_{12}T+D_{11}Tr)
\end{aligned} \tag{6.18}
$$

$$
\begin{aligned}
Y = {} & A_3+A_{31}(W_1/W_2)+A_{33}(P/W_2)+B_{31}Ia \\
& +B_{32}Ta+C_{31}R+C_{32}T+D_{31}Tr
\end{aligned} \tag{6.19}
$$

The symmetry condition $A_{13}=A_{31}$ will be tested.

b) The Generalized Leontief Profit Function

Similarly, a Generalized Leontief profit function is

$$
\begin{aligned}
\pi = {} & \alpha_0+\alpha_1 W_1^{1/2}W_2^{1/2}+\alpha_2 W_1^{1/2}P^{1/2} \\
& +\alpha_3 W_2^{1/2}P^{1/2}+\delta_1 W_1 Ia+\delta_2 W_1 Ta \\
& +\delta_3 W_1 R+\delta_4 W_1 T+\delta_5 Tr \\
& +\delta_6 W_2 Ia+\delta_7 W_2 Ta+\delta_8 W_2 R \\
& +\delta_9 W_2 T+\delta_{10} W_2 Tr+\delta_{11} P\ Ia \\
& +\delta_{12} P\ Ta+\delta_{13} P\ R \\
& +\delta_{14} P\ T+\delta_{15} P\ Tr
\end{aligned}
\tag{6.20}
$$

Then Hotelling's lemma implies the following input demand and rice supply equations:

$$
\begin{aligned}
F = {} & -(A_1+A_{12}(W_2/W_1)^{1/2}+A_{13}(P/W_1)^{1/2}+B_{11}Ia \\
& +B_{12}Ta+C_{11}R+C_{12}T+D_{11}Tr)
\end{aligned}
\tag{6.21}
$$

$$
\begin{aligned}
L = {} & -(A_2+A_{21}(W_1/W_2)^{1/2}+A_{23}(P/W_2)^{1/2}+B_{21}Ia \\
& +B_{22}Ta+C_{21}R+C_{22}T+D_{21}Tr)
\end{aligned}
\tag{6.22}
$$

$$
\begin{aligned}
Y = {} & A_3+A_{31}(W_1/P)^{1/2}+A_{32}(W_2/P)^{1/2}+B_{31}Ia \\
& +B_{32}Ta+C_{31}R+C_{32}T+D_{31}Tr
\end{aligned}
\tag{6.23}
$$

Symmetry conditions i.e., $A_{13}=A_{31}$, $A_{12}=A_{21}$, and $A_{23}=A_{32}$ will be tested.

6.3.1.3 Estimation Procedure

The two systems of input demand and output supply equations, as specified in terms of the Normalized Quadratic and the Generalized Leontief functional forms, will be estimated using the iterative version of Zellner's seemingly unrelated regression (ITSUR) method assuming the error terms are additive, independently and identically distributed with zero means. The symmetry restrictions implied by static competitive profit maximization are tested. If the hypothesis of symmetry is not rejected, a model will be estimated with symmetry imposed.

Parallel to what discussed in Chapter 3, the economic value or the shadow price of irrigation water within the dual context can be determined by the profit associated with a marginal increase in rice irrigated area. Note that from the present dual specification, by holding total rice area and other exogenous variables at the constant level, increasing irrigated rice area by 1 unit implies supplying irrigation water to an acreage of existing non-irrigated rice area. Since increasing irrigation by 1 unit may result in changes in the level of variable inputs used as well as output, the economic value of irrigation can then be calculated from the marginal revenue of rice output less marginal costs of fertilizer and labour.

From the Generalized Leontief specification (6.21)-(6.23), the shadow price of irrigation water can be evaluated as follows:

$$\begin{aligned} \partial\pi/\partial Ia &= P\partial Y/\partial Ia - W_1\partial F/\partial Ia - W_2\partial L/\partial Ia \\ &= B_{31}P - B_{11}W_1 - B_{21}W_2 \end{aligned} \tag{6.24}$$

where P, W_1, and W_2 represent the average rice farm price, fertilizer and labour, respectively.

Unlike the Generalized Leontief, the shadow price of irrigation cannot be directly derived from the estimating equations as above for the Normalized Quadratic since the labour demand equation (as the numeraire input) was excluded from the estimation process. Thus the demand equation for labour corresponding to (6.17) must be estimated or a demand equation for labour analogous to (6.18) can be estimated assuming a Quadratic profit function normalized on W_1. In either case the shadow price of irrigation can be computed as in (6.24).

SUR assumes that all explanatory variables in the model are exogenous or predetermined. However, farmers may simultaneously decide on rice acreage allocations (Ia, Ta) and on levels of variable inputs. Thus the model should be estimated by three stage least squares (3SLS) allowing for endogeneity of Ia and Ta. The set of instrumental variables for iterative 3SLS estimation consists of all exogenous variables included in the model, lagged total paddy land (Lpad), and lagged prices of alternative wet season crops (maize (LPc), groundnuts (LPg), soybeans (LPs), and mungbeans (LPm)).

In the case of the Normalized Quadratic, it is feasible (in terms of degrees of freedom) to estimate the dual function (6.17) jointly with factor demand (6.18) and output supply (6.19) when all restrictions on coefficients across (6.17) and (6.18)-(6.19) are imposed. The complete model is then estimated using ITSUR. The shadow price of irrigation water in this case can be derived by differentiating the profit function (6.17) with respect to irrigated rice acreage (Ia):

$$\partial\pi/\partial Ia = \alpha_3+\beta_2(W_1/W_2)\beta_7 P/W_2+\beta_{12}Ta+\beta_{13}R +\beta_{14}T+\beta_{15}Tr+2\delta_3 Ia \qquad (6.25)$$

Unlike the primal analysis, the impacts of irrigation on outputs and variable inputs can be easily derived within the dual context. In particular, the impacts of irrigation on fertilizer demand, labour demand and rice supply are obtained by differentiating the corresponding equations with respect to Ia.

Details on variable definitions, units of measurement, sources of data and time series data of variables used in estimating the wet season dual model are included in Appendix B and C.

6.3.2 Dry Season Rice Production

The dual models for dry season rice production are similar to the above models for the wet season. The one difference is that rice production generally requires irrigation in the dry season. This implies that Ia and Ta are identical. Therefore the only modification of wet season models is deletion of Ta. For the dry season model, the set of instrumental variables employed in the iterative 3SLS estimation include all exogenous variables, lagged prices of alternative dry season crops (similar to the wet season), lagged total paddy land, and lagged rice output in the wet season.

Fertilizer demand and rice supply equations assuming the Normalized Quadratic profit function (with labour wage as numeraire) are

$$F_d = -(A_1 + A_{11}(W_1/W_2) + A_{13}(P_d/W_2) + B_{11}Ia_d + C_{11}R + C_{12}T + D_{11}Tr) \tag{6.26}$$

$$Y_d = A_3 + A_{31}(W_1/W_2) + A_{33}(P_d/W_2) + B_{31}Ia_d + C_{31}R + C_{32}T + D_{31}Tr \tag{6.27}$$

The system of input demand and rice supply equations for the Generalized Leontief profit function is

$$F_d = -(A_1 + A_{12}(W_2/W_1)^{1/2} + A_{13}(P_d/W_1)^{1/2} + B_{11}Ia_d + C_{11}R + C_{12}T + D_{11}Tr) \quad (6.28)$$

$$L_d = -(A_2 + A_{21}(W_1/W_2)^{1/2} + A_{23}(P_d/W_2)^{1/2} + B_{21}Ia_d + C_{21}R + C_{22}T + D_{21}Tr) \quad (6.29)$$

$$Y_d = A_3 + A_{31}(W_1/P_d)^{1/2} + A_{32}(W_2/P_d)^{1/2} + B_{31}Ia_d + C_{31}R + C_{32}T + D_{31}Tr \quad (6.30)$$

The available time series data in the dry season dual analysis is more limited than in the wet season. The period of estimation is 1975 to 1990. Details on variable definitions, and time series data of variables used in estimating the dry season dual model are given in Appendix B and C.

6.4 Summary

Both primal and dual models of production are specified for national time series data in rice production. Various empirical models are discussed.

Chapter 7. Empirical Results: Farm Level Analysis

7.1 Introduction

This chapter presents results obtained from the farm level analysis for the HMO irrigation project in crop year 1991/92. Econometric results of shadow prices and impacts of irrigation are discussed.

7.2 Results for the Economic Value of Irrigation Water

7.2.1 Wet Season Analysis: Value of Irrigation Water in Rice Production

The OLS results for the initial wet season rice production model as specified in (5.1), using both linear and semilogarithmic functional forms, are reported in Table E.1, Appendix E. Coefficient estimates were more significant for the linear model than for the semilogarithmic model. Irrigated rice land (A), seed quantity (S), and number of tractor hours (Tr) were statistically significant at the 99 percent level, while fertilizer (F) and expenses on herbicide and insecticide (Hi) were significant at the 90 percent level. In the initial specification, aggregate total labour (L) and all dummy variables were statistically insignificant.

The model was alternatively reestimated by disaggregating labour variable into types and activities as previously discussed in Chapter 5.[1] In the case of labour employed during different time periods, there appeared to be a close relationship between the amount of fertilizer (F), herbicide and insecticide (Hi) and the labour associated with

[1] The marginal product of labour may vary by type and activity, and different farmers employ those categories of labour in different proportions. Consequently, disaggregation of the total labour variable may reduce errors in specification of the production function. Note that the disaggregation of labour variable into types and activities was employed separately in estimation of production functions.

the application of these inputs (L3).[2] Since they are highly complementary inputs, it was decided to regard L3 as in fixed proportion with F and Hi. As a result, L3 was omitted from the estimating model.

Similarly, labour employed in land preparation (L1) might be in fixed proportion to rice planting area (A). However, this need not be the case: land preparation involves plowing and also building or repairing dikes around a paddy field to store flood water necessary for growing rice, and these labour activities are not in fixed proportion. Thus L1 was tentatively included in the model as a separate input. In addition, labour employed during planting and harvesting periods (L2 and L4, respectively) were also included in the model since both activities normally occur during peak periods when labour shortages are significant (this encourages substitution away from labour during these periods, if possible). By disaggregating labour into activities, labour employed during harvesting season (L4) was significant at the 99 percent level.

Labour was also disaggregated into types (family, hired and exchange labour), hired labour (Lh) was statistically significant at the 99 percent level. However, dummy variables for both high yielding rice varieties (HYVs) and land ownership remained insignificant in both cases.

The insignificance of the dummy variable for seed suggests that the traditional rice varieties and the HYVs did not have different impacts on rice production. This may not be surprising because the HYVs require proper management practices in order to realize theirs highest potential. The relatively low level of average input use as shown in Table

[2] These considerations seemed to be supported by the high correlation between these variables in the data set (as shown in Table E.2, Appendix E).

A.2, Appendix A may support these results. For instance, the labour employed during fertilizer application, herbiciding and insecticiding, on average, accounted for only 6 percent of total labour employed for the entire rice production process (i.e., from land preparation to rice harvesting).

Similarly, the insignificant impact of land ownership on rice production may be explained by similarities in management practices between the owner-operated and tenant farmers in the survey area. Although the use of modern rice inputs (fertilizer, herbicide and insecticide) is more common on owner-operated farms, rice yield was only 5 percent higher for owner-operators than for tenants (Table A.3, Appendix A).

Table 7.1 provides OLS estimates of the final model where wet season rice production was specified as a linear function of rice planting area (A), seed quantity (S), tractor hours (Tr), expenses on herbicide and insecticide (Hi), and total labour employed during rice harvesting season (L4).[3] Hi was significant at the 95 percent level while all other variables were highly significant at the 99 percent level. Notice that hired labour (Lh) was omitted from the final model because it was highly correlated with the L4 variable. The results of the Glejser test and the Durbin-Watson (D.W.) statistic indicated that neither heteroskedasticity or autocorrelation was present in the model.

As shown in Table 7.1, the OLS estimate for marginal productivity of irrigated land in rice production was 293.38 kilogram per rai, which was substantially less than the average rice yield of 601.82 kilogram per rai obtained in the survey area (Table A.2, Appendix A). A 95 percent confidence interval for this marginal product (assuming a

[3] The model was also estimated using a quadratic functional form but results were poor due to multicollinearity.

normal distribution for the estimator) is 202.73 to 384.03 kilogram per rai.

Table 7.1 Estimates of Linear Wet Season Rice Model (Equation (5.1)) & Computed Production Elasticities of Respective Inputs

Variable	Estimate	T-ratio	Computed Production Elasticity
Constant	49.04	0.25	-
A	293.38	6.45***	0.507
S	15.94	2.90***	0.201
Tr	24.15	3.02***	0.114
Hi	0.84	2.01**	0.015
L4	11.34	2.65***	0.118
Adjusted R^2	77.41		
Chi-square (Glejser test)	7.610		
D.W.	2.10		

*** statistically significant at 99 percent
** statistically significant at 95 percent

The elasticities of production of the respective inputs were further evaluated at the means of the variable inputs and rice output. As shown in Table 7.1, the estimated elasticity of rice output with respect to irrigated land was 0.51. With the sum of the elasticities of all the variables close to unity (0.96), the data were compatible with constant returns to scale in rice production. According to Euler's Theorem, a constant returns to scale production function is consistent with the estimated marginal productivity of irrigated rice land being substantially less than its average productivity.[4]

By treating expenses on herbicide and insecticide (Hi), number of tractor hours (Tr)[5] and labour employed during harvesting season (L4) as endogenous variables, the final model was re-estimated using 2SLS. The instrumental variables employed included total farm land, lagged rice area, and lagged rice production.[6] In 2SLS estimation, rice planting area was treated as a quasi-fixed input since only 20 percent of total farm land was rented. Moreover, rice is customarily planted in the wet season regardless of prices of alternative crops, provides that there is sufficient water. This is mainly for farm consumption over the year, and only a relatively small amount of rice is marketed. Alternative wet season crops are also unattractive in the survey area due to difficulties of irrigation water management and other farm practices.[7] Seed quantity was treated as

---

[4] If a production function Y=f (X) is constant returns to scale, (i.e., homogeneous of degree one) and each input is paid in accordance with its marginal productivity, then by Euler's theorem

$$Y = f_1 X_1 + \sum_{i \neq 1} f_i X_i \tag{7.1}$$

where Y and X represent level of output and input, respectively, and f_i denotes marginal productivity of input i. Rearranging,

$$\frac{Y}{X_1} = f_1 + \sum_{i \neq 1} f_i \frac{X_i}{X_1} \tag{7.2}$$

[5] Even though less than half of the rice farmers in the sample owned tractors, the rest normally obtained land preparation by hiring tractor services. This suggested that most farmers at least could appropriately decided when to employ the tractor services for their land preparations. Thus there was possibility that the tractor variable may be contemporaneously related with the left out variables such as managerial ability presumably reflected in the error term.

[6] Since the disturbances are not autocorrelated, lagged endogenous variable is qualified for being employed as an instrumental variable.

[7] Flooding irrigation is typically employed in wet season rice production. Upland crops are not appropriate since they may be subjected to unwanted water from nearby rice fields.

exogenous since it was in approximately fixed proportion with land, which was treated as a quasi-fixed variable.[8]

The results, as reported in Table E.3, Appendix E, were unsatisfactory in terms of significance of the estimates. The t-values were dramatically lower for 2SLS than for OLS: none of the coefficients (including rice planting area) was statistically significant. This reflects the limited choice of instrumental variables in the present estimation, i.e., the data set presumably does not include the most important exogenous variables influencing endogenous input levels. For instance, output and input prices are excluded from the model due to insufficient variation over the cross section data set. Thus the selected instrumental variables were not highly correlated with the endogenous regressors. Moreover, the asymptotic properties of instrumental variable estimators may be poorly approximated for our small data set (for detail discussions and references, see for example, Judge et al., 1988, and Kmenta, 1990). Under these circumstances, the OLS estimator is preferred to 2SLS on the mean square error basis. Hence, the economic value of irrigation water in wet season rice production will be further analyzed only in terms of OLS estimates.

As discussed in Chapter 5, the marginal value of wet season irrigation in the HMO irrigation project area can be calculated by subtracting non-irrigated land rent from the marginal value of irrigated land in producing rice.[9] Table 7.2 presents the estimated

---

[8] A correlation matrix of all input uses in wet season rice production is provided in Table E.2, Appendix E.

[9] The average land rent of 500 baht per rai for crop year 1991/92, as estimated by agricultural officials and farmers in Sankampang district, was used to proxy the opportunity cost of non-irrigated agricultural land.

marginal value of irrigation water and its 90 and 95 percent intervals evaluated at the mean farm price for rice in the survey.[10] When the land rent of 500 baht per rai was employed to proxy the opportunity cost of non-irrigated land, the estimated marginal return to irrigation for wet season rice was 673.52 baht per rai,[11] and the 95 percent interval ranged from 310.91 to 1,036.13 baht per rai. Of course, the estimated marginal value of irrigation may be biased upward if soil fertility is higher on irrigated land than on non-irrigated land. No substantial variation in soil fertility was observed in the survey.

It is also important to note that these estimated results have focused on the average farm that received water from the HMO irrigation system. However, in examining the marginal value to irrigation water, not only the average but variations around the average are relevant. In other words, optimal use of irrigation water on average may not indicate optimal use on each individual farm. For instance, farms near the main regulators may enjoy excessive water while farms located at the end of the distributional canals suffer from water shortages. Yet the examination of marginal productivity of irrigation water on average may not address these significant differences.[12]

---

[10] It is worth reemphasizing that the marginal value of irrigation computed in this study only represents the private shadow price, i.e., the returns or benefits from irrigation to the farmer. Consequently, the farm price of rice is appropriate in calculating this shadow price because in such a small community both producers and consumers in effect trade at this price, i.e., this price represents the marginal value of rice in both production and consumption.

[11] Given the average field irrigation water requirement for wet season rice production (i.e., the traditional glutinous rice variety) in the HMO irrigation project area of 723.2 cubic metre (derived from Sir Alexandar Gibbe & Partners, 1981, Table MO12), the estimated marginal return per rai of irrigated land is equivalent to 0.93 baht per cubic metre. A 95 percent confidence interval is 0.43 to 1.43 baht per cubic metre.

[12] A technical point regarding this issue is worth mentioning. Exclusion of a distance variable in this study (i.e., distance from the farm to the main regulator or the main irrigation canal) did not seem to result in biased estimates of productivity of irrigated land. Although data on distance was not collected, the author's subjective impression was that the amount of irrigated rice land for a farm did not vary with

Table 7.2 **Computed Marginal Physical Product (MPP) of Irrigated Land and Marginal Value (MV) of Irrigation Water in Wet Season Rice Production, the HMO Irrigation Project**

MPP/MV	Estimate
MPP of irrigated land (kilogram/rai)	
Mean	293.38
90% interval	217.56-369.20
95% interval	202.73-384.03
MV of irrigation water[1] (baht/rai)	
Mean	673.52
90% interval	370.23-976.81
95% interval	310.91-1,036.13

[1] An average land rent of 500 baht per rai was employed to proxy the opportunity cost of non-irrigated land. The marginal value of irrigation water is calculated as: (1991 farm price of rice * MPP of irrigated land) - 500.

7.2.2 Dry Season Analysis: Garlic Production

The initial specification for a garlic production function (5.4) was estimated by OLS assuming that the underlying technology were characterized by linear and semilogarithmic functional forms. The estimated coefficients for the two models are reported in Table E.4, Appendix E. Again, t-ratios for estimated coefficients were higher for the linear functional form. There was no indication of heteroskedasticity or autocorrelation for either model, using Glejzer and Durbin-Watson tests.

distance. In other words, even if the distance variable does significantly affect crop yield in the survey area, exclusion of this variable does not bias estimates of the average marginal value of irrigation. On the other hand, more efficient estimators of the marginal product of irrigated land would have been obtained by including distance in the econometric model (assuming that distance influences yield).

The dummy variable for land ownership (DUM_O) was statistically insignificant; whereas seed quantity (S), total labour (L), and land (A) were significant in garlic production. The dummy variable and other insignificant inputs (i.e., fertilizer and expenses on herbicide and insecticide) were judged to be jointly insignificant using the Gallant and Jorgenson chi-square test.

The model was, therefore, reestimated with those variables omitted. As shown in column A of Table 7.3, all estimates of the remaining variables, i.e., planting area (A), seed quantity (S), and total labour (L) were highly significant. The model was further estimated by disaggregating the labour variable in the same manner as in the previous wet season rice models. However, only labour employed during land preparation period (L1) was significant. Note that a high correlation of almost 0.9 (Table E.5, Appendix E) between labour employed during land preparation and harvesting periods (L1 and L4, respectively) suggested that the estimated coefficient of L1 may reflect the influence of L4 as well as L1 on garlic production. The final model when total labour (L) was replaced by labour employed during land preparation (L1) is reported in column B, Table 7.3.[13] Comparing columns A and B, higher t-values for coefficient estimates were obtained when L was replaced by L1.

[13] The final model was also estimated using Cobb-Douglas (C-D), modified translog and modified quadratic functional forms (see Table E.6, Appendix E). The results for the C-D estimates were comparable to those using a linear form but less satisfactory in terms of t-ratios. The results for both modified translog and quadratic were poor due to multicollinearity.

Table 7.3 Estimates of Linear Dry Season Garlic Model (Equation (5.4))

Variable	A		B	
	Estimate	T-ratio	Estimate	T-ratio
Constant	-55.29	-0.52	5.50	0.63E-01
A	431.15	5.39***	386.90	6.20***
S	1.81	4.14***	2.12	6.35***
L	8.26	2.94***	-	-
L1	-	-	43.09	4.73***
Adjusted R^2	75.51		77.12	
Chi-square (Glejser test)	4.604		1.056	
D.W.	2.14		2.10	

*** statistically significant at 99 percent

The model was reestimated using 2SLS with seed quantity and labour employed during land preparation defined as endogenous variables primarily because the paucity of instruments limits the number of variables that can be defined as endogenous. Land was treated as quasi-fixed in the dry season. Total farm land and lagged garlic production were used as instrumental variables.

As shown in Table E.7, Appendix E, it is obvious that the variances of coefficient estimates were substantially higher for 2SLS than for OLS. All variables included in the model i.e., land (A), seed quantity (S), and labour employed during land preparation period (L1) were statistically insignificant using 2SLS. Of most importance, the t-ratio for the land variable fell from 5.39 for OLS to 0.59 for 2SLS. These poor results for 2SLS presumably reflect the weak correlation between the instrumental and the endogenous variables. Thus only OLS estimates will be considered in calculating marginal returns to irrigation.

As shown in Table 7.4, the estimated marginal physical product of irrigated land for garlic production in the 1992 dry season was 386.90 kilogram per rai, which was considerably less than the average product of 1,455.48 kilogram per rai (Table A.4, Appendix A). The corresponding marginal value of irrigation water evaluated at the average market price of fresh garlic in the 1992 dry season was 2,011.88 baht per rai,[14] and the 95 percent confidence interval ranged from 1,230.64 to 2,793.12 baht per rai. This expected value was almost three times higher than that of wet season rice. However, note that garlic farm prices have fluctuated greatly in comparison to rice prices.

7.2.3 Inverted Transformation Function

An inverted transformation function was specified for four particular crops (shallot, groundnuts, soybeans, and cucumbers) grown in the 1992 dry season in the HMO irrigation project area.[15] A multiple crop transformation function was modelled primarily because there was insufficient information to estimate separate production functions for each of these crops.

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[14] This was about 3.68 baht per cubic metre given the total field irrigation water requirement of 547.2 cubic metre (derived from Sir Alexandar Gibbe & Partners, 1981, Table MO12). A 95 percent interval ranges from 2.14 to 5.10 baht per cubic metre.

[15] A summary of production profile of the four selected crops is given in Tables A.5-A.8, Appendix A.

Table 7.4 Computed Marginal Physical Product (MPP) of Irrigated Land and Marginal Value (MV) of Irrigation Water in Dry Season Garlic Production, the HMO Irrigation Project

MPP/MV	Estimate
MPP of irrigated land (kilogram/rai)	
Mean	386.90
90% interval	262.79-511.01
95% interval	236.66-537.14
MV of irrigation water (baht/rai)	
Mean	2,011.88
90% interval	1,366.51-2,657.25
95% interval	1,230.64-2,793.12

The initial model where land was specified as a function of the four crop outputs, fertilizer, labour, and the expense on herbicide and insecticide (5.6) was estimated by OLS assuming both linear and semilogarithmic functional forms. As reported in Table E.8, Appendix E, the econometric results of the two functional forms employed were quite similar. All four crop outputs, i.e., shallot, groundnuts, soybeans, and cucumbers were significant at least at the 95 percent level, which implied significant positive relationships between planting areas and crop outputs. Only aggregate labour appeared to have significant impact jointly with land in producing the selected four crop outputs. Fertilizer (F) and expense on herbicide and insecticide (Hi) were statistically insignificant separately and jointly.

After omitting the insignificant variables (F and Hi), the model was reestimated and results are presented in Table 7.5. All output variables had a positive sign and were significant at the 95 percent level or higher for the linear functional form. The results obtained using the semilogarithmic form were comparable to those of the linear form except that aggregate labour was only significant at the 90 percent level. However, in the present inverted transformation function analysis, disaggregating labour variable into types and activities did not significantly improve results; so aggregate labour was retained in the final model.

Table 7.5 OLS Estimates for the Final Inverted Transformation Model (Equation (5.6))

Variable	Linear		Semilogarithmic	
	Estimate	T-ratio	Estimate	T-ratio
Constant	0.40	1.00	-0.22	-1.05
Y1	0.30E-02	2.63**	0.16E-02	2.59**
Y2	0.21E-01	2.92***	0.13E-01	3.33***
Y3	0.36E-01	9.90***	0.12E-01	6.52***
Y4	0.24E-02	2.84**	0.12E-02	2.72**
L	0.19E-01	2.09**	0.81E-02	1.74*
Adjusted R^2	66.26		52.37	
Chi-square (Glejser test)	4.259		6.49	
D.W Statistic	1.83		2.41	

*** statistically significant at 99 percent
** statistically significant at 95 percent
* statistically significant at 90 percent

A quadratic flexible form was also attempted assuming disjoint outputs. The hypothesis of disjoint technologies cannot be rejected by farm level data since few farmers produced more than one crop at a time: 23 farmers grew the four selected crops in the 1992 dry season, but 3 farms planted two crops while the rest planted only one crop at a time. When disjoint outputs were assumed, the quadratic form of the implicit production function was specified by deleting all interaction terms among the four outputs. As reported in Table E.9, Appendix E, the results was less than satisfactory. Only outputs of shallot and soybeans (Y1 and Y3, respectively) were significant at the 95 percent level.

Finally, the inverted transformation function where land was specified as a linear function of the four selected outputs and the aggregate labour was estimated by 2SLS. The estimating equation was just identified by employing lagged outputs of the four selected crops and the total farm land as instrumental variables. In the present context, lagged outputs seemed appropriate for instrumental variables since current output is often specified as dependent on past output (e.g., as in Nerlove partial adjustment or adaptive expectations models).

Table E.10, Appendix E provides 2SLS estimates of the final inverted transformation function. Again, the significance of coefficient estimates was substantially reduced when 2SLS was employed. Only soybeans output (Y3) was significant at the 95 percent level. The results indicate that the available instrumental variables provide a poor approximation to reduced form equations for crop outputs Y_1-Y_4. Accordingly, the OLS estimates were again selected for further calculations of the marginal value products of irrigation.

Table 7.6 presents the marginal physical product (MPP) and the marginal value (MV) of irrigated land in producing the four joint outputs i.e., shallot (Y1), groundnuts (Y2), soybeans (Y3) and cucumbers (Y4). The marginal productivity of irrigated land in producing each crop was computed as $(\partial A/\partial Y_i)^{-1}$, i.e., as the inverse of the partial derivative of land with respect to each crop output. The computed values of the marginal product of land in the production of shallot, groundnuts, soybeans and cucumbers were 333.33, 47.62, 27.78, and 416.67 kilogram per rai, respectively. Then marginal value of irrigated land were computed using 1992 average farm price of each crop. The calculated economic value of irrigated land for shallot, groundnuts, soybeans and cucumbers were 1,333.32, 314.29, 194.46 and 833.34 baht per rai, respectively.[16] The calculated shadow price for these four crops was lowest for soybeans and highest for shallot production.

Table 7.7 summarizes the computed mean value of the private shadow price (i.e., the marginal value of irrigated land) in producing different crops in the HMO irrigation project area, crop year 1991/92. There are substantial variations in marginal returns across crops. The highest value of 2,011.88 baht per rai was for production of garlic in the dry season. This was 10 times larger than the marginal return in production of soybeans in the dry season, which provided the lowest return.

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[16] Given the total field irrigation water requirement for (dry season) groundnuts and soybeans of 547.2 cubic metre per rai (derived from Sir Alexandar Gibbe & Partners, 1981, Table MO12), the estimated shadow prices of irrigated land for groundnuts and soybeans production are equivalent to 0.57 and 0.36 baht per cubic metre, respectively. Since comparable data on field irrigation water requirements for shallot and cucumbers production in the HMO irrigation project area are not available, the per volume shadow prices for shallot and cucumbers are not provided.

Table 7.6 **Computed Values of Marginal Physical Product (MPP) of Irrigated Land and Marginal Value (MV) of Irrigation Water Using the Final Inverted Transformation Model, the HMO Irrigation Project**

Crop	MPP of Irrigated Land (kilogram/rai)	MV of Irrigation Water (baht/rai)
Shallot	333.33	1,333.32
Groundnuts	47.62	314.29
Soybeans	27.78	194.46
Cucumbers	416.67	833.34

Table 7.7 **Summary of Computed Marginal Value (MV) of Irrigation Water in the HMO Irrigation project, Crop Year 1991/92**

Crop	MV of Irrigation Water (baht/rai)
Wet Season	
Rice	673.52
Dry Season	
Garlic	2,011.88
Shallot	1,333.32
Groundnuts	314.29
Soybeans	194.46
Cucumbers	833.34

The equality of marginal values of irrigation across crops are tested.[17] Except for soybeans, most estimates of shadow prices lie within the 95 percent confidence interval of the shadow prices for alternative crops. These can be roughly divided into 3 groups: high returns (garlic, shallot, and cucumbers), medium returns (rice and groundnuts) and low returns (soybeans). The 95 percent confidence interval for the shadow prices mainly occur within the same group. However, there is some overlap between groups, for example, the estimated shadow price of wet season rice lies within the 95 percent interval of cucumbers (Table 7.8).

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[17] Note that the marginal physical product of irrigated land in producing shallot, groundnuts, soybeans and cucumbers was computed as the inverse of the partial derivative of land with respect to crop output $(\partial A/\partial Y_i)^{-1}$ from the inverted transformation model. To test the equality of the marginal value of irrigation across crops, the 95 percent confidence interval of the inverse marginal product of irrigation for crop i $(\partial A/\partial Y_i)$ was compared with the product of the estimated inverse marginal product of crop j and the relative price ratio of the two crops. In other words, assuming identical marginal value products of irrigated land for crops i and j,

$$P_i/\hat{\beta}_i = P_j/\hat{\beta}_j \rightarrow \hat{\beta}_i = P_i\hat{\beta}_j/P_j$$

where $\hat{\beta}_i = \partial A/\partial Y_i$ and P_i=average farm price of crop i ($i \neq j$). Then a 95 percent confidence interval for the estimator $\hat{\beta}_i$ is compared with the estimate $P_i\hat{\beta}_j/P_j$.

Table 7.8 Comparisons of Marginal Value Products of Irrigation Across Alternative Crops

Crop i	Estimate of $\hat{\beta}_i$[a]	95 Percent Confidence Interval (CI) for $\hat{\beta}_i$	Average Farm Price (P) (Baht/ kg.)	Other Crops j with Similar Marginal Value Products[b]
Shallot	0.03E-02	0.59E-03-0.54E-02	4	Cucumbers, Garlic
Groundnuts	0.21E-01	0.58E-02-0.04	6.6	Soybeans, Cucumbers, Rice
Soybeans	0.36E-01	0.28E-01-0.04	7	-
Cucumbers	0.19E-01	0.62E-03-0.42E-02	2	Shallots, Rice, Garlic

[a] Partial derivative of irrigated land with respect to crop output i.

[b] Estimate of $p_i\hat{\beta}_j / p_j$ lies within a 95% CI for $\hat{\beta}_i$ (see footnote 17).

7.3 Results for the Impacts of Irrigation on Output and Variable Input

The impacts of irrigation on output and input levels will be illustrated using Cobb-Douglas results for garlic production in the dry season. Comparative static effects cannot be calculated (i.e., are undefined) for a linear production function.[18] As reported in Table E.6 of Appendix E, the estimated Cobb-Douglas garlic production model is

$$Y_G = 214.86\, A^{0.6} S^{0.23} L_1^{0.19} \qquad (7.3)$$

where Y_G and A represents the 1992 dry season garlic production and its planting area,

[18] The results of the estimates obtained for dry season garlic production model using linear and Cobb-Douglas were quite similar as presented in the previous section. The linear functional form was finally chosen only because of the relative higher t-ratios.

respectively. S and L_1 denote seed quantity and labour employed during land preparation.

Assuming static competitive profit maximization, the profit maximizing level of seed and labour demand equations can be derived by solving FOC for an interior solution. Given the estimated garlic production function (7.3), the reduced form demand equations for seed (S) and labour employed during land preparation period (L_1) are[19]

$$S = \left(\frac{0.23}{W_S}\right)^{1.40}\left(\frac{0.19}{W_{L1}}\right)^{0.33}\left(214.86P\,A^{0.6}\right)^{1.72} \tag{7.4}$$

$$L_1 = \left(\frac{0.23}{W_S}\right)^{0.40}\left(\frac{0.19}{W_{L1}}\right)^{1.33}\left(214.86P\,A^{0.6}\right)^{1.72} \tag{7.5}$$

where W_S , W_{L1} , and P represent price per unit of garlic seed, wage rate for labour employed during land preparation period and garlic farm price, respectively.

The impacts of irrigation on seed quantity demand and employment during land preparation for garlic are derived by differentiating (7.4) and (7.5) with respect to the land variable (A).[20] Given mean values of input prices, garlic farm price, and average garlic planting area (Tables A.1 and A.4, Appendix A), the impacts of irrigation on seed quantity demand and labour demand during the land preparation period would be 56.11 kilogram per rai and 7.94 man-days per rai, respectively.[21]

Allowing all the variable inputs (seed quantity and labour) to be adjusted to their

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[19] For an illustration of the derivation of profit maximizing input demand equations, see Henderson and Quandt, 1980.

[20] In the present analysis, note that since dry season crops can be produced only on irrigated land (with a sufficient irrigation water supply), the impact of land on garlic production can be attributed to irrigation.

[21] These computed values can be compared with the average seed quantity use of 34.70 kilogram per rai and the average of 4.21 man-days of labour during garlic land preparation period (Table A.4, Appendix A).

optimal levels, the impact of irrigation on garlic production can be computed by differentiating the estimated production function (7.3) with respect to the land variable (A). Substituting the optimal levels of seed quantity and labour inputs, an impact of irrigation on garlic output equals to 357.98 kilogram per rai, which is substantially less than the average production of 1,455.48 kilogram per rai (Table A.4, Appendix A).

7.4 Summary

This chapter has presented and discussed empirical results for the HMO irrigation project area located in the northern region of Thailand. Results were based entirely on the primal approach.

Chapter 8. Empirical Results: National Level Analysis

8.1 Introduction

This chapter presents results obtained from the analysis of national data. Results are obtained using both primal and dual methods. Econometric results of shadow prices and impacts of irrigation are discussed.

8.2 Results for the Economic Value of Irrigation Water

8.2.1 Wet Season Rice Production

8.2.1.1 Primal Model

Models were estimated using national data for crop years 1969/70 to 1990/91. Two-stage least squares estimates of the Cobb-Douglas functional form apparently provided better results (in terms of significance of coefficients) for wet season rice production than did modified Translog and Quadratic functional forms. Aggregations of several inputs other than land were attempted using both Laspeyres and Tornqvist quantity indexes. However, aggregation was possible only for the period from 1978 to 1990 when data on all input prices were available. Thus aggregation did not increase degrees of freedom or in turn increase significance of coefficients.

Results for the first model, where wet season rice production on irrigated and non-irrigated land were estimated separately (Equations (6.5) and (6.6)), are presented in Table 8.1a and 8.1b. As shown in Table 8.1a, column A, only irrigated land, number of tractors, and time trend were highly significant for rice production on irrigated land. Zero autocorrelation was not rejected using the Durbin-Watson (D.W.) test.

Table 8.1a Estimates of Wet Season Irrigated Rice Production Function (Cobb-Douglas Functional Form): Model I (Equation (6.5))

Variable	Initial Specification (A)		Insignificant Variables Deleted (B)	
	Estimate	T-ratio	Estimate	T-ratio
Constant	-16.313	-2.75**	-14.157	-2.74**
lnF	0.008	0.09	-	-
lnL_{1a}	0.192	1.15	-	-
lnERM	-0.15	-0.68	-	-
lnIa	2.387	4.14***	2.324	4.17***
lnTr	0.175	3.48***	0.153	3.81***
Tt	-0.04	-2.53**	-0.041	-3.08***
Adjusted R^2	88.97		90.80	
D.W. Statistic	1.983		1.828	

*** statistically significant at 99 percent
** statistically significant at 95 percent

The Gallant and Jorgenson chi-square test was employed to test for the joint significance of fertilizer, labour, and effective rainfall. The hypothesis of zero joint impact was not rejected so these variables were deleted from the model. As shown in column B, the elasticity of rice output with respect to irrigated land was estimated as 2.32. The negative coefficient for the time trend suggests either technical regress or omission of major inputs that are negatively correlated with a time trend. Another possible explanation is that the average quality of land may be decreasing as more marginal land is cultivated over time.

For non-irrigated (i.e., rainfed) rice production in the wet season, only rainfall and land are significant (Table 8.1b, column A). The presence of autocorrelation suggests that the equation is misspecified. Several variations in functional form did not eliminate the autocorrelation. Therefore, the original model was re-estimated by the Cochrane-Orcutt iterative process (CORC) in an attempt to correct for autocorrelation. As shown in column C, only average annual effective rainfall and non-irrigated rice planting area were significant. The elasticity of rice output with respect to non-irrigated land was estimated as 1.16.

Table 8.1b Estimates of Wet Season Rainfed Rice Production Function (Cobb-Douglas Functional Form): Model I (Equation (6.6))

Variable	Initial Specification (A)		Insignificant Variables Deleted (B)		Autocorrelation Corrected (C)	
	Estimate	T-ratio	Estimate	T-ratio	Estimate	T-ratio
Constant	-10.730	-3.32***	-10.863	-4.29***	-11.275	-4.49***
lnF	0.178	1.30	-	-	-	-
lnL_{Na}	-0.199	-0.99	-	-	-	-
lnERM	1.152	3.81***	1.025	4.55***	1.106	5.01***
lnNa	1.103	3.27***	1.176	7.92***	1.159	9.25***
lnTr	0.071	0.83	-	-	-	-
Tt	-0.033	-1.51	-	-	-	-
Adjusted R^2	74.49		76.59		78.57	
D.W. Statistic	2.492		2.662		2.282	

*** statistically significant at 99 percent
** statistically significant at 95 percent

Results of the estimates of the second wet season rice production model (Equation (6.7)) are presented in Table 8.2. From this model, total rice production in the wet season was significantly influenced by average annual effective rainfall, both irrigated and non-irrigated land, number of tractors, and time trend. All variables except the time trend were significant with the expected sign. The Durbin-Watson statistic indicated autocorrelation. Estimates of the model using CORC are indicated in column C of Table 8.2. The irrigated and non-irrigated land elasticities were estimated as 0.71 and 0.47, respectively.

Table 8.2 Estimates of Wet Season Rice Production Function (Cobb-Douglas Functional Form): Model II (Equation (6.7))

Variable	Initial Specification (A)		Insignificant Variables Deleted (B)		Autocorrelation Corrected (C)	
	Estimate	T-ratio	Estimate	T-ratio	Estimate	T-ratio
Constant	-12.941	-2.54**	-12.699	-2.79**	-7.566	-5.40***
lnF	0.133	1.43	-	-	-	-
lnL_l	-0.042	-0.30	-	-	-	-
lnERM	0.707	3.44***	0.585	3.21***	0.663	5.48***
lnIa	1.095	2.14*	1.145	2.30**	0.707	4.43***
lnNa	0.501	2.24**	0.638	3.72***	0.469	5.45***
lnTr	0.133	2.20**	0.086	1.87*	0.092	4.68***
Tt	-0.041	-2.39**	-0.024	-1.94*	-0.015	-3.03**
Adjusted R^2	74.49		76.59		78.57	
D.W. Statistic	2.586		2.689		2.109	

*** statistically significant at 99 percent
** statistically significant at 95 percent
* statistically significant at 90 percent

Results for the final primal model, i.e., model III (Equation (6.8)) are presented in Table 8.3. This model differs from model II by replacing the non-irrigated area planted to rice (model II) with total area planted to rice. The two models yielded similar results. CORC estimates of the final model are shown in column C. The elasticity of rice output with respect to irrigated land was estimated as 0.56. Since total land is another variable in the model, this elasticity can be interpreted as the estimated effect of substituting irrigated for non-irrigated land on supply of rice. In addition, total rice planting area, effective rainfall, tractors, and time trend were significant. All variables except for the time trend showed the anticipated sign.

In models I and II, the marginal product of irrigation water is computed as the difference between marginal products for irrigated and non-irrigated land, as previously discussed in Chapter 3. As shown in Table 8.4, elasticity estimates for irrigation water varied from 0.56 (model III) to 1.73 (model I). The marginal productivities of irrigation in increasing wet season rice production for the three models were very close, i.e., 766.18 kilogram per rai for model I, 661.05 kilogram per rai for model II and 666.11 kilogram per rai for models III.

As in the farm level analysis, the economic value of irrigation in producing wet season rice can be computed from the marginal value of irrigation given the market price of rice output. The marginal value of irrigation computed from the three primal models and its 90 percent confidence interval is presented in Table 8.5. The marginal values or shadow prices of irrigation calculated from model I, II, and III were 1,688.79, 1,457.06 and 1,468.20 baht per rai, respectively.

Table 8.3 **Estimates of Wet Season Rice Production Function (Cobb-Douglas Functional Form): Model III (Equation (6.8))**

Variable	Initial Specification (A)		Insignificant Variables Deleted (B)		Autocorrelation Corrected (C)	
	Estimate	T-ratio	Estimate	T-ratio	Estimate	T-ratio
Constant	-13.287	-2.63**	-13.153	-2.89**	-7.938	-5.47***
lnF	0.134	1.44	-	-	-	-
lnL_1	-0.043	-0.31	-	-	-	-
lnERM	0.707	3.44***	0.585	3.21***	0.663	5.39***
lnIa	0.936	1.76*	0.945	1.84*	0.564	3.17***
lnTa	0.659	2.24**	0.837	3.72***	0.614	5.37***
lnTr	0.133	2.19**	0.085	1.86*	0.092	4.65***
Tt	-0.041	-2.40**	-0.024	-1.95*	-0.016	-3.04**
Adjusted R^2	85.24		88.70		95.73	
D.W. Statistic	2.580		2.684		2.112	

*** statistically significant at 99 percent
** statistically significant at 95 percent
* statistically significant at 90 percent

Table 8.4 **Estimates of Elasticity and Marginal Physical Product (MPP) of Irrigation Water in Wet Season Rice Production and theirs 90 Percent Interval**

Model	Variable	Elasticity	90 Percent Interval	MPP (kg./rai)	90 Percent Interval (kg./rai)
I	Irrigated area	2.324	1.356-3.292	1,032.434	602.607-1,462.261
	Non-irrigated area	1.159	0.942-1.376	266.252	216.444-316.204
	Irrigation water	1.728	0.977-2.479	766.182	386.163-1,146.057
II	Irrigated area	0.707	0.429-0.985	834.994	506.090-1,163.898
	Non-irrigated area	0.469	0.319-0.619	173.945	118.254-229.635
	Irrigation water	0.638	0.510-1.276	661.049	387.836-934.263
III	Irrigation water	0.564	0.254-0.874	666.106	299.466-1,032.746

Table 8.5 **Computed Marginal Values of Irrigation in Wet Season Rice Production: Primal Approach**

Unit: Baht/rai

Model	Estimate	90% Interval
I	1,688.79	851.16-2,526.09
II	1,457.06	854.85-2,059.26
III	1,468.20	660.07-2,276.33

8.2.1.2 Dual Model

For wet season rice production, systems of fertilizer and labour input demands and rice supply equations were estimated for Normalized Quadratic and Generalized Leontief models as specified in Equations (6.18)-(6.19) and (6.21)-(6.23), respectively. Several specifications were considered for the expected price of rice output (marketed in year t): a one year lag in farm price (P_{t-1}), a three year moving average, and current year farm price (P_t). A one year lag provided the best fit and is emphasized here. The Normalized Quadratic provided a better fit than the Generalized Leontief. Therefore, the final results presented in this section will be based on the Normalized Quadratic form (econometric results for the initial model specification of the Generalized Leontief are reported in Appendix F).

Econometric results for the Normalized Quadratic model obtained by iterative seemingly unrelated regression (ITSUR) are presented in Table F.1, Appendix F. Estimates of the initial specification where fertilizer demand and rice supply were specified as functions of fertilizer price, lagged farm price for rice, irrigated rice area, total rice area, number of tractors, effective rainfall, and time trend are shown in column A. The tractor variable was insignificant in both fertilizer demand and rice production equations (see D11 and D31). As shown in column B, the t-ratio for the remaining parameters was slightly improved when number of tractors was excluded from the model. However, coefficients of the time trend in the rice supply equation (C32) remained negative and significant (as in the primal analysis).

Column C of Table F.1 presents parameter estimates when the time trend was also deleted. This led to a substantial change in results. Of most importance, the estimated coefficient of irrigated land (B31) fell from 2.76 in column B to 0.83 in column C. In addition, the low Durbin-Watson statistic indicated positive autocorrelation in the fertilizer demand equation. These results suggested that the time trend is correlated with important variables omitted from the model. Therefore it was decided to retain the time trend in the model.

As shown in column A of Table 8.6, the own price effect for fertilizer (A11) was not significant at the 90 percent level. This is not surprising since low fertilizer response rice varieties (i.e., traditional and improved traditional varieties) are still commonly grown in the wet season. In contrast, the own price effect for rice supply (A33) was positive and statistically significant. Concerning cross price effects, lagged farm price of rice had a significant positive impact on fertilizer demand (see A13), as expected. Fertilizer price did not have a significant influence on rice production (see A31).

Irrigated rice area had a significant positive impact on rice supply but not on fertilizer demand (see B31 and B11, respectively). Except for the coefficient of the time variable (C32) in the rice supply equation, all coefficients which were significant at the 90 percent level had the expected signs.

The Gallant and Jorgenson procedure chi-square test was employed to test for the reciprocity restriction implied by static competitive profit maximization. For the model selected, reciprocity was not rejected at the 95 percent level. However, it should be noted that one of the cross price coefficients (A31) was insignificant in the unrestricted model. This suggests a relatively high probability for a type II error, i.e., the hypothesis of symmetry may easily be accepted when it is false.

Table 8.6 ITSUR Estimates for the Final Wet Season Rice Model Using the Normalized Quadratic Functional Form (Equations (6.18)-(6.19))

Parameter	All Coefficients (A)		Symmetry Restriction Imposed (B)	
	Estimate	T-Ratio	Estimate	T-Ratio
A1	1208836.73	1.73	1163477.93	1.71
A11	-635942.54	-0.91	-609313.97	-0.89
A13	-3391.56	-2.52**	-3320.47	-2.53**
A3	-36956.53	-4.34***	-35300.87	-4.41***
A31	1762.72	0.21	-	-
A33	31.904	1.95*	36.485	2.53*
B11	13.851	0.22	15.856	0.25
B12	-13.176	-2.11*	-12.810	-2.10*
B31	2.758	3.56***	2.787	3.62***
B32	0.359	4.72***	0.328	5.86***
C11	381.148	1.94*	373.103	1.94*
C12	-52371.1	-3.22***	-52428.17	-3.30***
C31	4.279	1.79	4.911	2.30**
C32	-532.403	-2.70**	-563.865	-2.98**
Variable	D.W. Statistic	Adjusted R^2	D.W Statistic	Adjusted R^2
F	2.051	89.90	2.035	90.33
Y	2.388	85.25	2.195	85.43

*** statistically significant at 99 percent
** statistically significant at 95 percent
* statistically significant at 90 percent

The model was also estimated using iterative three stage least square (IT3SLS) treating irrigated and total rice land as endogenous variables. Column A of Table F.2, Appendix F provides IT3SLS estimates of the initial specification of the Normalized Quadratic model. Results were similar to those using ITSUR but somewhat less significant. However, the tractor variable was significant at the 90 percent level in the rice supply equation for IT3SLS (see D31). As shown in column B, the significance of coefficients decreased substantially when the time trend was excluded from the model. As in the previous model, it was decided to retain the time trend (Table 8.7).[1]

Estimation of the dual profit function equation jointly with the fertilizer demand and rice supply equations was also attempted. This required imposition of all across-equation restrictions implied by Hotelling's lemma and reciprocity. The econometric results as presented in Table F.5, Appendix F were poor. Most parameter estimates (especially those restricted to the profit equation) were not statistically significant. Due to the poor results and obvious difficulties, this approach is not considered further.

As discussed in Chapter 6, the value of irrigation water in the present dual model can be computed by calculating the difference between the impacts of irrigation on revenues and costs. The impacts of irrigated rice area on labour demand are reported in Table F.6. These results were obtained by estimating a Normalized Quadratic model as in Equations (6.18)-(6.19), treating fertilizer price as the numeraire.[2]

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[1] For comparisons, the ITSUR and IT3SLS estimates for the initial specification of the wet season rice production model using the Generalized Leontief functional form are given in Table F.3 and F.4, Appendix F, respectively.

[2] Note that the Normalized Quadratic specification when the labour demand equation was excluded in the estimation process generally gave more significant parameter estimates and higher adjusted R^2 than those with the exclusion of fertilizer equation. This may be due to the more accurate data set on fertilizer as noted earlier.

Table 8.7 **IT3SLS for the Final Wet Season Rice Model Using the Normalized Quadratic Form (Equations (6.18)-(6.19))**

Parameter	All Coefficients (A)		Symmetry Restriction Imposed (B)	
	Estimate	T-Ratio	Estimate	T-Ratio
A1	1364222.3	1.13	1407917.81	1.19
A11	-1060101	-1.03	-1061541.31	-1.05
A13	-3326.08	-1.86*	-3504.84	-2.01*
A3	-15177.35	-1.09	-22288.12	-2.27**
A31	-13085.89	-1.10	-	-
A33	50.923	2.45**	41.977	2.64**
B11	29.481	0.36	26.813	0.33
B12	-18.65	-1.85*	-19.077	-1.93*
B31	1.82	1.91*	1.980	2.34**
B32	0.221	1.89*	0.298	4.74***
C11	469.706	1.94*	482.346	2.04*
C12	-56756.13	-2.38**	-55729.58	-2.38**
C31	4.837	1.73	3.828	1.69
C32	-800.135	-2.89**	-702.311	-3.12**
D11	-0.153	-0.06	-0.256	-0.10
D31	0.053	1.82*	0.042	1.81
Variable	D.W Statistic	Adjusted R^2	D.W Statistic	Adjusted R^2
F	2.313	88.01	2.328	88.47
Y	2.266	84.13	2.477	87.02

*** statistically significant at 99 percent
** statistically significant at 95 percent
* statistically significant at 90 percent

However, the estimated coefficient of irrigated land was insignificant in both fertilizer and labour demand equations (see B11 in column A, Tables 8.6 and 8.7 and B21 in Table F.6). This suggests that changes in irrigated land (holding total rice land and other explanatory variables in the system of estimating equations constant) did not induce changes in the level of either fertilizer or labour used in production. Therefore in this special case, the marginal physical product of irrigation was computed as the marginal impact of irrigation on output supply.

Table 8.8 reports shadow prices for irrigation computed from the final ITSUR and IT3SLS estimates (reciprocity is not imposed). The shadow price of irrigation obtained from IT3SLS estimates was significantly lower than shadow prices from ITSUR. In other words, the computed values from one estimator lay outside the 90 percent confidence interval for the other estimator.

Table 8.8 Computed Marginal Value of Irrigation Water in Wet Season Rice Production: Dual Approach

Unit: Baht/rai

Estimator	Mean Value	90 % interval
ITSUR	7,519.43	7,515.49-7,523.37
IT3SLS	4,962.06	4,957.94-4,966.18

As shown in Table 8.5 and 8.8, the shadow price of irrigation in wet season rice production derived from the primal and dual analyses differ substantially. In principle these two approaches should provide similar results under similar assumptions, but estimates for the two approaches may differ substantially when there are serious errors in specification of the two models. For example, consistent estimation of the marginal physical product requires only consistent estimates of land coefficients in the primal production function but requires consistent estimates of land coefficients in all three output and input equations. In addition, the technologies implicit in the primal and dual model estimated here are quite different.

Estimates of the shadow price of irrigation seem more reasonable in the case of the primal than in the dual analysis. However, the presence of autocorrelation in most models and the negative significant coefficients for a time trend suggest that models are misspecified.

8.2.2 Dry Season Rice Production

8.2.2.1 Primal Model

The primal analysis of dry season rice production generally yielded unsatisfactory results. First a Cobb-Douglas functional form for Equation (6.13) was estimated by 2SLS. As shown in Table F.7, Appendix F, all parameters estimated except the coefficient of rice irrigated area were statistically insignificant. These results may be due to multicollinearity or inadequate variation of the regressors in the data set. The correlation matrix for explanatory variables (reported in Table F.8, Appendix F) showed high correlation coefficients of 0.8-0.9 among several variables (rice irrigated area, fertilizer, number of tractors, and time trend). Therefore both Laspeyres and Tornqvist aggregate quantity indexes were constructed from fertilizer and tractor variables, but this did not lead to more significant results. Omission of one (or more) of the collinear variables also did not reduce the variance of estimated coefficients for the remaining variables.

Modified Quadratic and Translog functional forms were also estimated, but results were insignificant (Table F.9, Appendix F).

Production function models were also estimated where the dependent variable was redefined as yield. This defines alternative transformation (functional form) regarding the production function. Rice yield in the dry season during the estimation period (1975-90) varied from 405.03 to 637.32 kilogram per rai, with mean and standard deviation of 547.58 and 58.27 kilogram per rai, respectively. Rice yield was specified as a function of rice irrigated area, labour, rainfall during the dry season, fertilizer, number of tractors per unit of rice area, and a time trend. Model results were unsatisfactory (see Table F.10, Appendix F): all estimates of coefficients (including the coefficient of rice irrigated area) were insignificant.

8.2.2.2 Dual Model

The dual approach led to more significant results than the primal in modelling dry season rice production with time series national data. Rice supply and fertilizer demand equations were specified assuming a Normalized Quadratic profit function (with the labour wage as numeraire price). ITSUR results are reported in column A, Table 8.9. Then rainfall and time trend were omitted from the initial model on the basis of a chi square test of joint significance.

As shown in column B of Table 8.9, the significance of the remaining variables was improved, but there is substantial autocorrelation. CORC estimates of this model are reported in column C. Coefficient estimates are similar to B but t-statistics are higher. The own price effect for fertilizer demand (A11) was significant at the 95 percent level with the expected sign, but the own price effect for rice output (A33) and cross price effects (A13 and A31) were statistically insignificant. Rice irrigated area had a significant positive impact on both fertilizer demand and rice output (B11 and B31, respectively) as expected. Number of tractors had a significant positive relation to fertilizer demand (see D11), which suggests that fertilizer and tractors are complements. Since cross price effects were statistically insignificant, reciprocity conditions were neither imposed nor tested.

The model was also estimated by IT3SLS treating total dry season rice area as endogenous. Table 8.10 reports IT3SLS estimates of the initial specification with rainfall and time trend omitted. IT3SLS results were similar to ITSUR, but t-values are somewhat lower for IT3SLS. Changes in the specification of instrumental variables did not change results. Rice output supply and labour demand equations were also estimated jointly assuming a Normalized Quadratic profit function with the price of fertilizer specified as the numeraire. ITSUR and IT3SLS joint estimates are reported in Table F.11, Appendix F.

A system of fertilizer and labour demand and output supply equations was also estimated assuming a Generalized Leontief profit function. Econometric results for the final model using ITSUR are presented in Table 8.11. The labour wage showed a significant positive effect on fertilizer rice demand (A12), but all other cross price effects were statistically insignificant. The coefficients of rice irrigated area were significant at the 99 percent level with positive signs for all the three equations. Results were consistent with those for the Normalized Quadratic model. IT3SLS results are reported in Table 8.12.

Table 8.9 ITSUR Estimates for the Final Dry Season Rice Model Using the Normalized Quadratic Form (Equations (6.26)-(6.27))

Parameter	All Coefficients (A)		(Non-price) Insignificant Variables Omitted (B)		Corrected for Autocorrelation(C)	
	Estimate	T-Ratio	Estimate	T-Ratio	Estimate	T-Ratio
A1	2299.44	0.05	-6685.05	-0.31	-16983.93	-1.18
A11	-248118.80	-1.36	226805.86	1.73	278088.80	2.68**
A13	-202.48	-0.61	-260.54	-1.01	-290.47	-1.58
A3	1322.73	0.89	309.46	0.46	292.44	0.43
A31	-4246.24	-0.77	-871.62	-0.22	-863.56	-0.21
A33	1.93	0.19	-1.62	-0.20	-1.48	-0.18
B11	-34.48	-6.53***	-35.64	-7.53***	-33.86	-9.04***
B31	0.50	3.11**	0.52	3.55***	0.52	3.56***
C11	-38.20	-0.68	-	-	-	-
C12	-630.61	-0.18	-	-	-	-
C31	1.26	0.74	-	-	-	-
C32	-82.06	-0.79	-	-	-	-
D11	-0.33	-1.93*	-0.42	-3.21***	-0.42	-4.97***
D31	0.07E-01	0.66	0.48E-04	0.01	0.01E-02	0.02
Variable	D.W. Statistic	Adjusted R^2	D.W Statistic	Adjusted R^2	D.W Statistic	Adjusted R^2
F_d	2.979	97.02	3.096	97.40	2.395	98.13
Y_d	2.021	77.47	1.890	79.68	1.885	79.68

*** statistically significant at 99 percent
** statistically significant at 95 percent

Table 8.10 **IT3SLS Estimates for the Final Dry Season Rice Model Using the Normalized Quadratic Form (Equations (6.26)-(6.27))**

Parameter	Insignificant Variables Deleted (A)		Corrected for Autocorrelation (B)	
	Estimate	T-Ratio	Estimate	T-Ratio
A1	-12620.54	-0.53	-46722.11	-1.94
A11	256586.41	1.83*	417000.47	2.58**
A13	-314.03	-1.14	-470.27	-1.72
A3	2.16	0.01	-165.39	-0.22
A31	670.24	0.15	1517.03	0.34
A33	-4.24	-0.48	-4.58	-0.52
B11	-32.70	-4.98***	-22.51	-2.94**
B31	0.67	3.21***	0.69	3.34***
D11	-0.47	-3.07**	-0.58	-4.04***
D31	-0.26E-02	-0.52	-0.24E-02	-0.48
Variable	D.W Statistic	Adjusted R^2	D.W Statistic	Adjusted R^2
F_d	3.123	97.30	1.983	96.19
Y_d	1.682	77.68	1.662	76.88

(A) Only insignificant non-price exogenous variables (i.e., rainfall conditions and time trend variable were omitted from the initial specification.

*** statistically significant at 99 percent
** statistically significant at 95 percent
* statistically significant at 90 percent

Table 8.11 ITSUR Estimates for the Final Dry Season Rice Model Using the Generalized Leontief Form (Equations (6.28)-(6.30))

Parameter	Insignificant Variables Deleted (A)		Corrected for Autocorrelation (B)	
	Estimate	T-Ratio	Estimate	T-Ratio
A1	54198.98	2.10*	54026.44	3.18***
A12	-12510.30	-0.96	-19941.82	-2.35**
A13	-792.49	-0.65	-320.48	-0.44
A2	-25449.70	-0.98	-22871.71	-0.91
A21	-23521.60	-0.35	-13295.07	-0.21
A23	-618.47	-0.23	-1163.55	-0.43
A3	-251.43	-0.25	-264.48	-0.26
A31	-2344.21	-0.09	-1738.65	-0.06
A32	3009.47	0.36	2809.67	0.33
B11	-36.25	-7.63***	-34.13	-10.01***
B21	-15.76	-4.75***	-16.37	-5.15***
B31	0.54	3.69***	0.54	3.70***
D11	-0.32	-1.66	-0.26	-2.20*
D21	0.25	2.51**	0.26	2.64**
D31	0.40E-04	0.01	0.11E-03	0.02
Variable	D.W Statistic	Adjusted R^2	D.W Statistic	Adjusted R^2
F_d	3.078	97.33	2.377	98.08
L_d	1.950	59.54	1.851	59.12
Y_d	1.884	79.37	1.877	79.36

(A) Only insignificant non-price exogenous variables (i.e., rainfall conditions and time trend variable were omitted from the initial specification.

*** statistically significant at 99 percent

** statistically significant at 95 percent

* statistically significant at 90 percent

Table 8.12 IT3SLS Estimates for the Final Dry Season Rice Model Using the Generalized Leontief Form (Equations (6.28)-(6.30))

Parameter	Insignificant Variables Deleted (A)		Corrected for Autocorrelation (B)	
	Estimate	T-Ratio	Estimate	T-Ratio
A1	59148.49	2.27**	60498.93	3.24***
A12	-16420.65	-1.23	-23153.50	-2.46**
A13	-613.51	-0.49	-396.94	-0.51
A2	-18635.44	-0.70	-15137.28	-0.57
A21	-53278.85	-0.77	-49185.50	-0.71
A23	289.86	0.10	-64.55	-0.02
A3	-375.24	-0.37	-382.61	-0.38
A31	508.51	0.02	789.86	0.03
A32	2626.80	0.31	2478.02	0.29
B11	-36.89	-7.52***	-33.13	-8.10***
B21	-17.27	-4.94***	-18.07	-5.25***
B31	0.55	3.71***	0.56	3.74***
D11	-0.26	-1.29	-0.24	-1.67
D21	0.26	2.56**	0.27	2.65**
D31	-0.37E-04	-0.01	-0.36E-04	-0.01
Variable	D.W. Statistc	Adjusted R^2	D.W. Statistc	Adjusted R^2
F_d	3.145	97.31	2.543	98.08
L_d	1.903	58.64	1.821	57.87
Y_d	1.858	79.34	1.847	79.32

*** statistically significant at 99 percent
** statistically significant at 95 percent

The shadow price of irrigation for dry season rice production can be computed from estimates of the dual model in the same manner as in Equation (6.24). Computed values are presented in Table 8.13. Except for ITSUR for the Normalized Quadratic, empirical estimates of this shadow price in dry season rice production were similar, ranging from 487.22 to 513.63 baht per rai.

Table 8.13 Computed Marginal Value of Irrigation Water in Dry Season Rice Production: Dual Approach

Unit: Baht/rai

Functional Form	Estimator	Mean Value	Variance	90 % interval
Normalized Quadratic	ITSUR	497.73	1,925.23	418.92-576.53
	IT3SLS	1,148.93	960.66	1,093.27-1,204.60
Generalized Leontief	ITSUR	513.63	1,997.81	433.36-593.91
	IT3SLS	487.22	2,029.74	406.31-568.14

As summarized in Table 8.14, estimates of the shadow price of irrigation vary considerably by season and by model. In the wet season analysis, estimates of the marginal value product of irrigation obtained by the primal approach varied from 1,457.06 to 1,688.79 baht per rai; whereas estimates obtained by the dual approach varied from 4,962.10 to 7,519.43 baht per rai.

For the dry season analysis, estimates of the marginal value of irrigation water obtained by the dual approach were relatively close, ranging from 487.22 to 1,148.93 baht per rai (Table 8.14). Shadow prices were not calculated by the primal approach due to the extremely poor fit of production functions for the dry season. Nevertheless econometric results suggest that the shadow price of irrigation is substantially lower in the dry season than in the wet season. A plausible explanation of this result can be summarized as follows. In the dry season rice production depends primarily on irrigation rather than on natural rainfall, whereas the reverse is true in the wet season. Moreover, in the wet season irrigation will primarily be used at critical times when natural rainfall is inadequate. In the most general terms, when an input (irrigation) is used in small quantities relative to other inputs (natural rainfall), then the marginal physical product of the input is likely to be relatively large (assuming diminishing marginal returns to an input).

Table 8.14 Summary of Computed Values of Irrigation Water in Rice Production at the National Level[1]

Unit: Baht/rai

Functional Form	Estimator	Wet season		Dry season	
		Computed value	90 percent interval	Computed value	90 percent interval
Primal approach					
C-D	2SLS	1,688.79	851.16-2,526.09	-	-
		1,457.06	854.85-2,059.26	-	-
		1,468.2	660.07-2,276.33	-	-
Dual approach					
Normalized Quadratic	ITSUR	7,519.43	7,515.49-7,523.37	497.73	418.92-576.53
	IT3SLS	4,962.06	4,957.94-4,966.18	1,148.93	1,093.27-1,204.60
Generalized Leontief	ITSUR	-	-	513.63	433.36-593.91
	IT3SLS	-	-	487.22	406.31-568.14

[1] Combined from Tables 8.5, 8.8 and 8.13

Of course the validity of these econometric results is contingent on the accuracy of the data and model specifications. The models have assumed a static rather than dynamic structure, risk neutrality, and disjoint technologies. These assumptions were adopted due to data limitations rather than their accuracy.

8.3 Results for the Impacts of Irrigation on Output and Variable Input

Impacts of irrigation on output supply and factor demand can be derived by simple differentiation output supply and input demand equations estimated within the dual context. Table 8.15 summarizes estimated impacts of irrigation on rice supply, fertilizer and labour demand in both wet and dry season rice production. Note that irrigation impacts on fertilizer and labour demand in the wet season model were not statistically significant. All other estimates were significant at least at the 90 percent level.

Table 8.15 Summary of the Estimated Impacts of Irrigation in Wet and Dry Season Rice Production: National Level Analysis[1]

Rice growing season	Functional form	Estimator	Fertilizer demand (kg./rai)	Labour demand (man-days/rai)	Rice supply (kg./rai)
Wet season	Normalized Quadratic	ITSUR	-15.86	0.77	2,787
		IT3SLS	-29.48	26.15	1,820
Dry season	Normalized Quadratic	ITSUR	33.86	15.62	520
		IT3SLS	22.51	12.99	690
	Generalized Leontief	ITSUR	34.13	16.37	540
		IT3SLS	33.13	18.07	560

[1] Combined from Tables 8.6, 8.7, 8.9-8.12 and Tables F.6, F.11, Appendix F.

As shown in Table 8.15, ITSUR and IT3SLS estimates of irrigation impacts in the wet season model imply that wet season rice output supply would increase by 2,787 or

1,820 kilogram per rai increase in irrigated land. By definition this supply response allows all other inputs to adjust to new static equilibrium levels. Since these supply responses are substantially higher than the average irrigated wet season rice yield of 450 kilogram per rai, the estimated change in output supply presumably reflects substantial increases in other inputs accompanying the change in irrigated land. However, as noted above, the estimated impacts of irrigated land on fertilizer and labour demand was statistically insignificant in the wet season.

Estimates of impacts of irrigation appeared to be more reasonable for the dry season rice production model. Estimates of impacts obtained from the two functional forms (i.e., the Normalized Quadratic and Generalized Leontief) using the two estimators (i.e., ITSUR and IT3SLS) were comparable. As reported in Table 8.15, irrigation showed significant positive impacts on both fertilizer and labour demand in dry season rice production. The effects of irrigation on dry season rice fertilizer and labour demand were between 22.51 and 34.13 kilogram per rai and 12.99 and 18.07 man-days per rai, respectively. The results implied that irrigation, fertilizer, and labour were complements in producing rice in the dry season.

Rice output supply in the dry season was estimated to increase by 520 to 690 kilogram per rai increase in irrigated land. Since these supply responses are comparable to the average dry season rice yield of 550 kilogram per rai, these results appear to be consistent with moderate impacts of irrigated land on input demands.

8.4 Summary

This chapter has summarized empirical results obtained from a time series of national level data. Results are based on both primal and dual models. The use of national data inevitably implies many errors in model specification, i.e., conditions for consistent aggregation over firms are unlikely to hold (Chambers, 1988). Thus results must be interpreted with considerable caution.

Chapter 9. Summary and Conclusions

9.1 Summary

The primary objective of this study is to estimate the value of water in irrigation and investigate the contribution of irrigation to the productivity of Thai agriculture. The analysis is conducted using both farm level data for a particular irrigation project and national level data. While the farm level analysis provides estimates of irrigation water productivity at the specific irrigation site, it is difficult to generalize from a single irrigation project to the nation. Therefore an analysis using national level data is also conducted despite inevitable errors in aggregation.

For the farm level analysis, the Huai Mae On (HMO) irrigation project located in Sankampang district, Chiang Mai province, North of Thailand was selected. Cross section survey data regarding agricultural production activities in the 1991 wet season (July to December) and 1992 dry season (January to June) was collected from 103 farmers in the HMO irrigation project area. For the national level analysis, time series data for rice production from crop year 1969/70 to 1990/91 and 1975 to 1990 were employed to estimate marginal returns to irrigation for wet and dry season, respectively.

Since data on the amount of irrigation water used in crop production could not be obtained for the farm level study and was not available at the national level, the productivity of irrigation water was approximated by the difference between the productivity of irrigated and non-irrigated land. The difference between irrigated and non-irrigated land productivities can provide a reasonable approximation to the productivity of irrigation if irrigated and non-irrigated land are similar in quality. This assumption can not be evaluated at the national level. On the other hand, casual observation suggests that this assumption may be appropriate in the vicinity of the HMO irrigation project (differences in soil quality between irrigated and non-irrigated land were not apparent).

In the present empirical study, static models were estimated assuming both primal and dual model specifications. Such models assume both a static (seasonal) production function and static decisions. Static models were adopted because there is little empirical knowledge of dated production functions or dynamic specifications.

One objective of the current study has been to extend the general theory of shadow prices for resource stocks in dynamic equilibrium and to compare shadow price formulas in static and dynamic models. Modifications of recent dynamic envelope theorems were developed to clarify the relations between formulas for shadow prices of resource stocks in static and dynamic models. These results indicate that, under certain circumstances, static measures of shadow prices for resource stocks may provide a rough approximation to dynamic measures.

In this study, farm level data was analyzed by estimating crop production functions. Production functions were estimated for wet season rice production and dry season garlic production. An inverted multi-output transformation function was also estimated for four dry season crops (shallot, groundnuts, soybeans and cucumbers) because there were insufficient observations to estimate each specific crop production function. Since there is little price variation in the cross section farm level data set, dual models of output supply and factor demand were not estimated with the farm level data.

Both primal and dual models were specified and estimated with the national level data. Due to data limitations, the national level analysis was restricted to rice production in both wet and dry seasons.

9.2 Research Findings and Policy Implications

9.2.1 Farm level analysis

Econometric results for production functions using farm level data suggest that there are substantial variations in returns to irrigation for different crops in the HMO irrigation project area in crop year 1991/92. Results suggest that garlic provides the highest return per unit of irrigated land as compared to wet season rice and other dry season crops (shallot, groundnuts, soybeans and cucumbers). Estimated shadow prices of irrigation vary substantially from 195 baht per rai for soybeans production to 2,010 baht per rai for garlic production.[1]

Nevertheless, in spite of these differences in estimated shadow prices of irrigation, most estimates of shadow price (marginal value of irrigation) for the dry season crops are within the 95 percent confidence interval of the shadow prices for alternative crops. However, Table 7.8 suggests that there are two major groupings of crops: (i) garlic, shallot and cucumbers and (ii) rice and groundnuts. The confidence interval for any of these crops generally contains the point estimates for marginal value products of other crops in the same group, but does not generally contain point estimates for crops outside

[1] Since data on irrigation water requirements for shallot and cucumbers in the HMO project area are not available, shadow prices of irrigation across crops are compared on the basis of area rather than volume. Note that water requirements for dry season upland crops and vegetables are not substantially different.

the group. These results may indicate inefficiencies in water allocation across groups.[2] Alternatively these results may be explained in part by risk aversion: marginal value products of irrigation are higher for crops in group (i) than in group (ii), but the variation in prices over time is also higher for crop in group (i) than in group (ii).

The high standard errors associated with the estimates, however, limits the inferences that can be drawn from econometric results. This may be due to model specification errors (e.g., errors in functional forms and omitted variables) and inaccuracies in data. In addition there are various problems associated with OLS and 2SLS estimation procedures as discussed earlier.

9.2.2 National level analysis

Econometric results with national level data show considerable variations in estimates of the marginal value of irrigation water, especially between the primal and dual approaches. Empirical results are especially peculiar for the wet season analysis. The estimated shadow prices of irrigation in wet season rice production at the national level vary between 1,457 and 1,689 baht per rai under the primal approach. Under the dual approach, they vary between 4,962 and 7,519 baht per rai. Such differences (between the primal and dual approaches) may be attributed to: (a) differences in the specification of technologies implicit in the primal and dual models and (b) specification errors which appear to be more critical in the dual models where shadow prices are calculated as the marginal profits associated with an increase in irrigation. In this study, only two variable

[2] As discussed in Chapter 3, the profit maximizing firm in static equilibrium would allocate water such that the marginal value products of irrigation in alternative crops are equal. In the two-period case, the first-order conditions imply that the marginal values of irrigation between the two periods differ only by the rate of interest (and any costs of storing water between the periods, such as evaporation losses).

inputs (i.e., fertilizer and labour) were employed. Other variable inputs were omitted due to lack of data. These specification errors suggest that the dual approach may tend to provide higher estimates of marginal returns to irrigation than will the primal approach.

Estimates of the shadow price of irrigation in wet season rice production obtained from the national level analysis are two to ten times higher than estimates from the wet season rice model using farm level data. A partial explanation for these differences may be in terms of land quality. Differences in land quality (between irrigated and non-irrigated land) appear to be minor in the vicinity of the HMO, but these differences may well be significant at the national level.[3] Since the shadow price of irrigation in the wet season is approximated by the difference between irrigated and non-irrigated land productivities, the relatively high shadow price of irrigation evaluated at the national level may reflect a significant difference in average quality of irrigated and non-irrigated land (for the entire nation).

In contrast, estimates of the shadow price of irrigation from various dry season rice models appear to be relatively robust (less variation as compared with the wet season). The shadow prices of irrigation for rice production in the dry season estimated by the dual approach are between 487 and 1,149 baht per rai. Note that shadow prices were not calculated by the primal approach due to the poor fit of the estimated production

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[3] As noted in Chapter 2, the geographical location of irrigation project in Thailand has been influenced not only by the availability of water supplies but also the quality of land. In the Northeast region of Thailand, poor soils (due to lack of moisture holding capacity) has resulted in a very low share of irrigation development in the region.

functions. These estimates are substantially lower than those in the wet season.[4] As explained earlier, the relatively low marginal physical productivity of irrigation in the dry season compared to wet season irrigation may be because more irrigation water is required for rice production during the dry season and diminishing marginal returns to increased irrigation. Substantial variation of the estimated shadow prices of irrigation between wet and dry season rice production may also suggest inefficient water allocation system between growing seasons. However, it may also be possible that the marginal returns to rice in the dry season may be relatively low as compared to wet season rice or specialty crops. Rice in the dry season may be produced mainly on irrigated land where diversification is not possible (e.g., land where irrigation was traditionally designed for rice or area with minimal water control)[5] so that more efficient allocation of water between seasons can not be obtained.

9.2.3 Policy Implications

Econometric results from the present study suggest that the marginal value of irrigation is positive (i.e., statistically different from zero) for both wet and dry seasons. This is consistent with the observation that irrigation projects place quantity restrictions, albeit not price restrictions (water is available at essentially zero price), on the allocation of water among users. However, there is no conclusive evidence that water is allocated

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[4] On the other hand, note that the estimate of shadow price of irrigation for dry season rice (obtained from a dual Normalized Quadratic model) lies within the 90 percent confidence interval of the estimated shadow price for the wet season (Cobb-Douglas primal models) (Table 8.15).

[5] This is supported by the survey data collected in the HMO irrigation project area where irrigated land in the dry season is generally planted to crops other than rice.

efficiently across crops and growing seasons.[6]

Most estimates of shadow prices of irrigated land for the HMO irrigation project area are associated with high variances which imply that hypotheses of equal marginal value products (or shadow prices) of irrigation for several alternative crops are not rejected despite large differences in point estimates. Nevertheless hypotheses of equality are generally rejected at the 95 percent level between crops with high returns (garlic, shallots and cucumbers) and crops with relatively lower returns (rice, groundnuts and soybeans). These results suggest inefficiencies in the allocation of irrigation water across some alternative crops within season and between growing seasons (or alternatively risk aversion). In principle these inefficiencies may be reduced by pricing irrigation water to users.[7]

9.3 Future Research

There are many conceptual and data problems with the present analysis. Of most importance, data on actual water use in production was unavailable at both the farm level and national level. The problem was bypassed by assuming that the difference between the marginal productivity of irrigated and non-irrigated land can be attributed to irrigation.

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[6] Results of significantly higher returns of irrigation in the wet season rice production than in the dry season (at the national level) suggest that irrigation water is not optimally allocated between seasons within static equilibrium framework. However, firm conclusions can not be obtained since the differences in productivity of irrigated and non-irrigated land in the wet season may also reflect the differences in land quality as emphasized earlier.

[7] Area-based fees, differentiated by types of crop (based on productivity of water), may influence water use through their effects on farmers' cropping decisions. However, careful analysis of the impacts of water charges on farmers' decisions is necessary before implementation. Note also that improved productivity of irrigated land through the introduction of other complementary inputs (including increased management skills) may make existing irrigation systems more profitable. However, this may not directly address the problem of inefficiencies in the allocation of water across crops and seasons.

To improve the accuracy of the results, it is important to incorporate variations in land quality (especially between irrigated and non-irrigated land) into the analysis. This is not feasible using national data, but information on soil quality can in principle be obtained at the farm level. At the farm level analysis, it may also be worth incorporating a distance variable (i.e., distance between farm and the main regulator) into the production model since it may partly determine availability of irrigation water at a particular site. It would also be useful to consider alternative methods for incorporating quality differences in other inputs such as fertilizer and labour. Disaggregating labour into men, women, and children with a prior weighting scheme of work intensity may also be appropriate.

The assumption of risk-neutral behaviour (on the part of farmers), which is implicit in all calculations of shadow prices, is questionable. Risk aversion implies that shadow prices should not be calculated as a marginal value product of irrigation, and specification of the duality models should be changed. Therefore, it may be more realistic to incorporate risk aversion into future analyses (e.g., a Just-Pope technology and/or a mean-variance duality model may be specified).

Whereas this study focuses on the private shadow price of irrigation, it is also important to calculate social net benefits of irrigation.[8] This requires that prices of outputs and all inputs in production be adjusted to reflect social benefits or opportunity costs. For instance, a rice premium (a tax on Thai rice exports) effectively kept the

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[8] It can provide insight into the profitability of the irrigation projects and can be used to formulate public policies necessary for efficient use of water such as water pricing and irrigation water development schemes.

domestic price of rice in Thailand well below that in world markets. As a result, the social value of rice output is higher than the farm price. Use of the actual farm price as a basis for valuation in this case will understate the social value of rice output, and hence understates the social value of irrigation water.

Finally, econometric estimates of crop production functions with irrigation may vary substantially across sites due to variations in climate and soils. Thus the present study should be replicated for different irrigation projects, and perhaps for the HMO irrigation project in different years. If there is sufficient data (including data on water use), then estimation of a dated production function might help to incorporate site-specific factors as well as the impact of timing of water applications into the analysis.

9.4 Conclusions

This chapter has summarized the main points of the study. Assuming a static structure and risk neutrality, the empirical results obtained from farm level analysis seem to be more reasonable than results from the national level analysis. The principal reason may be because variations in physical and climatic conditions (especially soil quality and weather) are significantly reduced in a single irrigation project area. In addition, more detailed information on factors influencing crop production can be obtained and incorporated into the farm level analysis.

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APPENDIX A.

Summary of Statistical Survey Data on Selected Crop Production

Table A.1 Summary of Survey Data on Input and Output Prices in the HMO Irrigation Project Area, Crop Year 1991/92

Variable	Number of obs.[1]	Unit	Average	Minimum	Maximum	Standard Deviation
Rice						
Rice farm price	47	baht/kg.	4	3.67	4.67	0.23
Seed	23	baht/kg.	7.3	7	10	0.77
Fertilizer	44	baht/50kg.	256	250	320	13.49
Herbicide	79	baht/15kg.	258.61	240	280	6.51
Land Prep.	37	baht/man-day	96.67	80	100	7.32
Planting	54	baht/man-day	63.06	50	80	6.41
Fertilizing	4	baht/man-day	80	80	80	0
Harvesting	47	baht/man-day	66.67	60	80	5.27
Garlic						
Garlic farm price	14	baht/kg.	5.2	5	7	0.6
Seed	1	baht/kg.	17	17	17	0
Fertilizer	19	baht/50kg.	344	300	350	13.86
Land prep.	4	baht/man-day	100	100	100	0
Planting	16	baht/man-day	79.17	70	100	10.94
Fertilizing	7	baht/man-day	90	70	100	11.95
Harvesting	14	baht/man-day	79.05	70	90	2.99
Shallot						
Shallot farm price	7	baht/kg.	4	3	5	0.71
Seed	1	baht/kg.	5	5	5	0
Fertilizer	7	baht/50kg.	357.14	350	380	11.61
Land prep.	2	baht/man-day	100	100	100	0
Planting	4	baht/man-day	60	50	70	10
Harvesting	5	baht/man-day	70	70	70	0

[1] Number of farms actually engaged in each activity (i.e., selling outputs or purchasing inputs).

(Cont'd)

Table A.1 Continued

Variable	Number of obs.	Unit	Average	Minimum	Maximum	Standard Deviation
Groundnuts						
Groundnuts farm price	5	baht/kg.	6.6	6	7	0.24
Seed	1	baht/kg.	7	7	7	0
Land prep.	1	baht/man-day	100	100	100	0
Planting	3	baht/man-day	56.67	50	60	7.53
Harvesting	4	baht/man-day	55	50	60	5
Soybeans						
Soybeans farm price	6	baht/kg.	7	7	7	0
Seed	5	baht/kg.	15.4	15	17	0.8
Fertilizer	1	baht/kg.	6	6	6	0
Land prep.	1	baht/man-day	100	100	100	0
Planting	6	baht/man-day	65	50	80	12.58
Harvesting	6	baht/man-day	66.67	50	80	11.06
Cucumbers						
Cucumbers farm price	8	baht/kg.	2	2	2	0
Fertilizer	6	baht/kg.	10	10	10	0
Land prep	1	baht/man-day	100	100	100	0
Planting	3	baht/man-day	73.33	60	100	18.86
Fertilizing	3	baht/man-day	60	60	60	0
Harvesting	2	baht/man-day	55	50	60	5

Table A.2 Summary of Survey Data on Wet Season Rice Production, the HMO Irrigation Project Area, Crop Year 1991/92

Variable	Unit	Average	Minimum	Maximum	Standard Deviation
Yield	kg./rai	601.82	240.52	1,288.50	184.95
Average input					
Rice planting area	rai/farm	5.22	1.50	13	2.47
Seed	kg./rai	8.09	2.86	40	4.38
Fertilizer	kg./rai	10.50	0	50	12.71
Herbicide& insecticide	baht/rai	29.76	0	250	43.95
Total labour	man-day/rai	14.42	4.60	46.50	39.22
Type of labour					
Own	man-day/rai	5.77	1	24	4.09
Hired	man-day/rai	5.09	0	20.20	4.10
Exchange	man-day/rai	3.56	0	42.50	5.70
Activity of labour					
Land preparation	man-day/rai	3.42	0.50	20	2.98
Planting	man-day/rai	3.90	0.40	12.50	1.18
Fertilizing	man-day/rai	0.92	0	2.83	0.76
Harvesting	man-day/rai	6.17	1.20	11.67	2.21
Cash expense					
Purchased inputs[1]	baht/rai	75.47	0	380	93.13
Hired labour	baht/rai	316.04	0	1470	281.87
Tractor service	baht/rai	164.28	0	600	174.38
Total	baht/rai	555.79	0	2107.20	352.67

[1] Including seed, fertilizer, herbicide and insecticide.

Table A.3 Summary of Wet Season Rice Production Characterized by Land Ownership, the HMO Irrigation Project Area, Crop Year 1991/92

Variable	Unit	Overall	Owner-operated	Tenant[1]
Yield	kg./rai	601.82	611.61	581.62
Average input				
Rice planting area	rai/farm	5.22	5.15	5.38
Seed	kg./rai	8.09	8.27	7.74
Fertilizer	kg./rai	10.50	11.50	8.44
Herbicide & insecticide	baht/rai	29.76	32.84	26.44
Total labour	man-day/rai	14.42	14.62	14.03
Type of labour				
Own	man-day/rai	5.77	5.34	5.49
Hired	man-day/rai	5.09	5.86	4.69
Exchange	man-day/rai	3.56	3.42	3.85
Activity of labour				
Land preparation	man-day/rai	3.42	3.07	4.16
Planting	man-day/rai	3.90	3.78	4.15
Fertilizing	man-day/rai	0.92	1.10	0.58
Harvesting	man-day/rai	6.17	6.67	5.14
Cash expense				
Purchased inputs	baht/rai	75.47	78.51	60.95
Hired labour	baht/rai	316.04	341.39	263.84
Tractor service	baht/rai	164.28	141.05	215.11
Total	baht/rai	555.79	560.95	539.90

[1] Including those who partially rented rice land.

Table A.4 Summary of Survey Data on Dry Season Garlic Production, the HMO Irrigation Project Area, Crop Year 1991/92

Variable	Unit	Average	Minimum	Maximum	Standard Deviation
Yield	kg./rai	1,455.48	1,100	2,400	381.07
Average input					
Planting area	rai/farm	2.11	0.50	6	1.48
Seed	kg./rai	34.70	18	56.67	8.55
Fertilizer	kg./rai	45.51	4	85	27.17
Herbicide& insecticide	baht/rai	124.18	0	400	131.89
Total labour	man-day/rai	23.17	15.67	60.00	8.07
Type of labour					
Own	man-day/rai	13.62	1	48	10.36
Hired	man-day/rai	9.55	0	27	6.85
Activity of labour					
Land preparation	man-day/rai	4.21	1	12	2.76
Planting	man-day/rai	6.86	0.67	17	4.09
Fertilizing	man-day/rai	4.43	1	12	3.10
Harvesting	man-day/rai	7.67	1.67	24	5.63
Cash expense					
Purchased inputs[1]	baht/rai	596.95	80	1,790	435.30
Hired labour	baht/rai	452.40	0	990	268.43
Total	baht/rai	1,049.35	80	2,210	567.27

[1] Including seed, fertilizer, herbicide and insecticide.

Table A.5 Summary of Survey Data on Dry Season Shallot Production, the HMO Irrigation Project Area, Crop Year 1991/92

Variable	Unit	Average	Minimum	Maximum	Standard Deviation
Yield	kg./rai	1,083.90	400	2,000	501.95
Average input					
Planting area	rai/farm	2.21	0.75	4	1.14
Seed	kg./rai	32.18	12.5	66.67	20.67
Fertilizer	kg./rai	30.93	6.67	75	23.56
Herbicide& insecticide	baht/rai	80.26	0	260	98.21
Total labour	man-day/rai	26.72	10.67	53.00	14.23
Type of labour					
Own	man-day/rai	18.47	4.73	42	14.44
Hired	man-day/rai	8.25	0	17	6.44
Activity of labour					
Land preparation	man-day/rai	5.65	3	6.67	1.47
Planting	man-day/rai	7.31	2.33	12.50	3.57
Fertilizing	man-day/rai	6.03	0.50	18	6.81
Harvesting	man-day/rai	7.73	1.67	12.50	3.45
Cash expense					
Purchased inputs[1]	baht/rai	300.24	125	545	162.68
Hired labour	baht/rai	493.79	0	1,050	449.92
Total	baht/rai	794.03	125	1,595	526.85

[1] Including seed, fertilizer, herbicicde and insecticide.

Table A.6 Summary of Survey Data on Dry Season Groundnuts Production, the HMO Irrigation Project Area, Crop Year 1991/92

Variable	Unit	Average	Minimum	Maximum	Standard Deviation
Yield	kg./rai	250.18	200	300	45.48
Average input					
Planting area	rai/farm	2.35	2	3	0.49
Seed	kg./rai	33.27	20	55	13.62
Fertilizer	kg./rai	-	-	-	-
Herbicide& insecticide	baht/rai	15.17	0	53.33	23.46
Total labour	man-day/rai	17.06	5.45	31.50	9.98
Type of labour					
Own	man-day/rai	9.81	2.55	24.50	9.05
Hired	man-day/rai	7.25	2.91	15.67	5.15
Activity of labour					
Land preparation	man-day/rai	4.14	2	10	3.33
Planting	man-day/rai	3.71	2	4.67	1.20
Fertilizing	man-day/rai	1.37	0	3.50	1.73
Harvesting	man-day/rai	7.84	2.18	14	5.39
Cash expense					
Purchased inputs[1]	baht/rai	85.17	0	403.33	178.13
Hired labour	baht/rai	464.09	145.45	940	301.03
Total	baht/rai	549.26	145.45	1,343.33	468.16

[1] Including seed, fertilizer, herbicicde and insecticide.

Table A.7 Summary of Survey Data on Dry Season Soybeans Production, the HMO Irrigation Project Area, Crop Year 1991/92

Variable	Unit	Average	Minimum	Maximum	Standard Deviation
Yield	kg./rai	211.76	151.40	300	49.91
Average input					
Planting area	rai/farm	5.71	4.75	8	1.29
Seed	kg./rai	15.66	6.42	30	7.99
Fertilizer	kg./rai	2.56	0	15.38	6.28
Herbicide& insecticide	baht/rai	71.34	0	187.50	71.65
Total labour	man-day/rai	8.85	6.74	12	8.85
Type of labour					
Own	man-day/rai	3.93	1	9.20	3.93
Hired	man-day/rai	4.92	2.80	6	1.13
Activity of labour					
Land preparation	man-day/rai	1.26	0.63	1.88	0.53
Planting	man-day/rai	2.75	1.85	4.40	0.99
Fertilizing	man-day/rai	1.29	0.13	3.60	1.32
Harvesting	man-day/rai	3.55	2.11	5.54	1.35
Cash expense					
Purchased inputs[1]	baht/rai	291.56	130	480	155.82
Hired labour	baht/rai	342.89	140	480	132.15
Total	baht/rai	634.45	406.32	950	216.32

[1] Including seed, fertilizer, herbicicde and insecticide.

Table A.8 Summary of Survey Data on Dry Season Cucumbers Production, the HMO Irrigation Project Area, Crop Year 1991/92

Variable	Unit	Average	Minimum	Maximum	Standard Deviation
Yield	kg./rai	2,128.57	1,250	3,350	791.55
Average input					
Planting area	rai/farm	1.79	0.5	4	1.15
Fertilizer	kg./rai	33.93	0	100	41.18
Herbicide&insecticide	baht/rai	34.29	0	150	61.06
Total labour	man-day/rai	21.36	11	42	10.85
Type of labour					
Own	man-day/rai	17.57	6.50	36	11.19
Hired	man-day/rai	3.79	0	8	3.03
Activity of labour					
Land preparation	man-day/rai	4.64	2.50	12	3.25
Planting	man-day/rai	3.43	1.50	8	2.32
Fertilizing	man-day/rai	8.86	3	18	5.21
Harvesting	man-day/rai	4.43	2	10	2.68
Cash expense					
Purchased inputs[1]	baht/rai	271.07	0	787.50	292.72
Hired labour	baht/rai	218.57	0	480	184.25
Total	baht/rai	489.64	0	1,127.50	425.95

[1] Including seed, fertilizer, herbicicde and insecticide.

APPENDIX B.

Details on Variable Definitions, Unit of Measurement, and Sources of Data Employed in the National Level Analysis

Table B.1 List of Variables Name, Definitions, and Unit of Measurement: Wet Season Rice Production (National Level Analysis)

Variable	Definition	Unit of Measurement
Y_{Ia}	Annual wet season rice production on irrigated land	1000 ton
Y_{Na}	Annual wet season rice production on non-irrigated land	1000 ton
Y	Total annual rice production in the wet season	1000 ton
Ia	Irrigated rice planting area in the wet season	1000 rai
Na	Rainfed rice planting area in the wet season	1000 rai
Ta	Total wet season rice planting area	1000 rai
F	Fertilizer (ammonium sulphate, urea, 16-20-0 and 16-16-8) applied to wet season rice production	ton
L	Total labour employed in wet season rice production	1000 man-day
L_{Ia}	Labour employed in wet season irrigated rice production	1000 man-day
L_{Na}	Labour employed in wet season rainfed rice production	1000 man-day
RM	Average annual rainfall	millimetre
ERM	Average effective annual rainfall	millimetre
WRM	Average annual rainfall during the wet season rice growing period (July-December)	millimetre
WERM	Average annual effective rainfall during the wet season rice growing period	millimetre
Tr	Number of agricultural tractors	unit
Tt	Time trend	1969=1
Lpad	One-year lagged total paddy area	1000 rai

(Cont'd)

Table B.1 Continued

Variable	Definition	Unit of Measurement
Ry_1	3-year moving average total wet season rice yield	kilogram/rai
Ry_{Ia}	3-year moving average irrigated rice yield in the wet season	kilogram/rai
Ry_{Na}	3-year moving average rainfed rice yield in the wet season	kilogram/rai
Qpump	Number of water pump	unit
Qeng	Number of machine-operated sprayers	unit
Qman	Number of hand-operated sprayers	unit
P_1	Farm price of rice in the wet season	baht/ton
W_1	Retail price of rice fertilizer in the wet season	baht/kilogram
W_2	Minimum wage rate	baht/day
Wpump	Retail price of water pump (pump size 4 inches, 5-6 Horse Power)	baht/unit
Weng	Retail price of machine-operated sprayers	baht/unit
Wman	Retail price of hand-operated sprayers	baht/unit
Wtrac	Retail price of tractor (MT., 77 Horse Power)	baht/unit
π	Annual Profit from wet season rice production (revenues less variable costs) normalized by labour input cost	1000 baht
LPc	One-year lagged farm price of maize	baht/kilogram
LPs	One-year lagged farm price of soybeans	baht/kilogram
LPg	One-year lagged farm price of groundnuts	baht/kilogram
LPm	One-year lagged farm price of mungbeans	baht/kilogram

Table B.2 List of Variables Name, Definitions, and Unit of Measurement: Dry Season Rice Production (National Level Analysis)

Variable[a]	Definition	Unit of Measurement
Y_d	Total annual rice production in the dry season	1000 ton
Ia_d	Rice planting area in the dry season	1000 rai
F_d	Fertilizer (ammonium sulphate, urea, 16-20-0 and 16-16-8) applied to dry season rice production	ton
L_d	Total labour employed in dry season rice production	1000 man-day
DRM	Average annual rainfall during the dry season rice growing period (January-June)	millimetre
Ry_d	3-year moving average dry season rice yield	kilogram/rai
LY	One-year lagged total wet season rice production	1000 ton
P_d	Expected dry season rice price	baht/ton

[a] Notations, definitions and measurement units of other common variables employed in the dry season model are similar to those given in Table B.1.

Table B.3 Sources of Data Employed in the National Level Analysis

Variable	Source
1) Ia, Ta, Y_{Ia}, Y_{Ta}	Irrigated Agriculture Branch, RID
2) Na, Y_{Na}	Calculated from Ta-Ia and Y_{Ta}-Y_{Ia} respectively
3) Y_d, Ia_d	*Agricultural Statistics Yearbook*, Office of Agricultural Economics, MOAC
4) F_I, F_d, W_1,, Qpump, Qeng, Qman, Wpump, Weng, Wman, Wtrac	Agricultural Economic Research Division, Office of Agricultural Economics, MOAC
5) P_I, P_d	*Agricultural Statistics Yearbook*, Office of Agricultural Economics, MOAC
6) W_2	Labour Department
7) L_I, L_{Ia}, L_{Na}, L_d	Calculated from dividing total labour cost (i.e., average labour cost (AL) times rice planting area) by agricultural wage rate (W_2).
8) AL	Agricultural Economic Research Division, Office of Agricultural Economics, MOAC
9) RM, DRM	Meteorological Department
10) Tr	*FAO Production Yearbook*

APPENDIX C.

Time Series Data Employed in the National Level Analysis

Table C.1 Data Employed in the Wet Season Primal and Dual Models: National Level Analysis

Year	Ia (1000 rai)	Na (1000 rai)	Ta (1000 rai)	Y_{Ia} (1000 ton)	Y_{Na} (1000 ton)	Y_{Ta} (1000 ton)
1969	11,263.1	36,466.9	47,730	4,309.641	9,040.359	13,350
1970	11,487.0	37,273.0	48,760	4,296.816	9,103.184	13,400
1971	11,712.5	38,307.5	50,020	5,029.973	9,170.027	14,200
1972	11,301.1	33,318.9	44,620	4,611.475	7,058.525	11,670
1973	11,385.4	36,184.6	47,570	5,028.634	8,901.367	13,930
1974	11,601.8	34,198.2	45,800	4,617.599	7,982.401	12,600
1975	11,761.2	40,808.8	52,570	4,739.323	11,020.677	15,760
1976	11,961.6	40,788.4	52,750	5,321.940	11,218.060	16,540
1977	12,134.2	40,355.8	52,490	5,492.729	6,787.271	12,280
1978	12,716.9	45,263.1	57,980	5,619.445	10,220.555	15,840
1979	12,847.8	44,792.2	57,640	5,927.034	9,462.966	15,390
1980	12,879.0	48,391.0	61,270	6,117.422	11,022.578	17,140
1981	13,233.1	46,296.9	59,530	6,232.554	10,477.446	16,710
1982	13,711.0	43,869.0	57,580	6,712.454	8,977.546	15,690
1983	14,064.4	52,615.6	66,680	6,209.711	13,600.289	19,810
1984	14,478.9	43,431.1	57,910	7,133.607	10,136.393	17,270
1985	14,886.9	44,553.1	59,440	7,427.615	10,502.385	17,930
1986	14,918.8	43,021.2	57,940	7,305.068	9,524.932	16,830
1987	15,107.0	38,803.0	53,910	7,037.070	8,232.930	15,270
1988	15,123.5	44,246.5	59,370	7,452.171	10,427.829	17,880
1989	15,550.1	44,419.9	59,970	7,702.979	10,347.021	18,050
1990	15,014.9	43,185.1	58,200	5,502.685	9,397.315	14,900
Mean	13,142.7	41,845.0	54,987.7	5,901.3	9,664.2	15,564.5
S.D.	1,513.1	4,719.7	5,741.5	1,106.3	1,489.9	2,115.4

(Cont'd)

Table C.1 Continued

Year	L_1 (man-day)	L_{Ia} (man-day)	L_{Na} (man-day)	P_1 (baht/ton)	W_1 (baht/ kg.)	W_2 (baht/ day)
1969	1,017,084	240,007	777,077	976.00	2.06	8.67
1970	1,175,358	276,894	898,464	843.00	2.14	8.67
1971	1,038,478	243,166	795,311	799.91	2.00	8.67
1972	1,044,392	264,518	779,874	1,311.05	2.18	11.00
1973	946,686	226,580	720,106	1,958.52	3.37	11.00
1974	687,797	174,229	513,568	2,232.25	5.00	17.25
1975	834,751	186,754	647,996	1,978.29	4.66	17.25
1976	919,960	208,610	711,350	1,844.22	3.10	17.25
1977	937,078	216,626	720,452	2,322.84	3.15	20.00
1978	915,078	200,706	714,371	2,186.97	3.24	26.50
1979	767,598	171,096	596,503	2,609.28	4.03	36.37
1980	757,795	159,289	598,506	3,067.97	5.02	45.50
1981	596,617	132,624	463,993	2,909.00	5.61	56.50
1982	579,515	137,995	441,521	2,942.00	5.28	56.88
1983	669,339	141,180	528,160	2,757.00	4.08	59.88
1984	577,330	144,346	432,984	2,299.00	4.13	59.88
1985	578,834	144,970	433,864	2,320.00	5.30	62.63
1986	538,694	138,707	399,988	2,408.00	4.93	64.75
1987	507,420	142,192	365,228	3,790.00	3.70	64.75
1988	545,668	139,000	406,669	4,092.00	4.18	66.50
1989	473,275	122,719	350,556	3,610.00	4.67	77.13
1990	473,154	122,068	351,086	3,748.00	4.58	77.13
Mean	753,722.8	178,830.7	574,892.1	2,409.3	3.9	39.7
S.D.	215,988.7	48,257.7	169,343.7	931.5	1.1	25.2

(Cont'd)

Table C.1 Continued

Year	F_1 (ton)	Tr (unit)	RM (millimetre)	WRM (millimetre)
1969	199,505	4,200	1,706.2	1,349.1
1970	168,415	4,700	1,864.7	1,448.1
1971	164,696	9,148	1,622.0	1,256.7
1972	228,038	10,946	1,540.1	1,270.8
1973	192,940	13,273	1,607.9	1,310.9
1974	132,597	15,993	1,659.3	1,268.2
1975	172,462	30,130	1,776.0	1,314.7
1976	270,802	30,300	1,627.1	1,274.3
1977	265,662	30,500	1,388.5	1,088.2
1978	291,365	33,000	1,603.7	1,214.8
1979	300,000	64,443	1,332.3	1,024.9
1980	320,000	73,335	1,629.0	1,331.4
1981	340,055	89,202	1,537.1	1,179.6
1982	373,851	107,528	1,483.2	1,153.1
1983	466,454	113,116	1,651.3	1,429.2
1984	443,808	120,918	1,489.4	1,136.0
1985	413,929	125,000	1,573.5	1,177.5
1986	447,857	130,000	1,541.9	1,176.0
1987	459,240	136,000	1,480.4	1,237.4
1988	611,000	142,000	1,746.0	1,306.1
1989	857,820	150,000	1,405.1	1,063.3
1990	739,400	157,000	1,499.6	1,117.2
Mean	357,268	72,306	1,580.2	1233.1
S.D.	189,436.1	55,335.1	129.0	111.9

(Cont'd)

Table C.1 Continued

Year	Qpump (unit)	Qeng (unit)	Qman (unit)	Wpump (baht/ unit)	Weng (baht/ unit)	Wman (baht/ unit)	Wtrac (baht/ unit)
1978	289,827	39,228	257,408	11,400	3,950	820	185,000
1979	332,666	45,058	316,405	12,013	4,304	813	220,000
1980	381,869	51,822	389,243	12,883	4,800	782	221,667
1981	438,382	59,679	479,268	12,883	5,000	862	232,500
1982	477,030	68,811	590,649	14,450	5,000	1,000	245,000
1983	519,106	79,434	728,606	14,450	5,000	1,000	258,583
1984	564,915	91,802	899,675	14,450	5,000	842	281,667
1985	614,791	10,6211	1,112,062	15,442	5,287	818	281,667
1986	669,095	12,3008	1,376,074	16,150	5,225	834	286,667
1987	768,328	14,2607	1,704,696	16,150	5,075	793	290,833
1988	851,349	16,5483	2,114,292	18,917	5,450	832	313,333
1989	943,387	19,2205	2,625,537	19,500	5,450	950	320,000
1990	1,101,850	22,3433	3,264,604	19,500	5,450	990	320,000
Mean	611,738.1	106829.	1,219,886.	15,245.	4,999.3	872	265,916.
S.D.	246,433.4	59107.4	955,192.2	2,733.4	444.7	81.8	42,688.5

Table C.2 Data Employed in the Dry Season Primal and Dual Models: National Level Analysis

Year	Y_d	Ia_d	F_d	DRM	P_d^a
1975	939	2,068	70,310	461.3	n.a.
1976	1,208	2,358	82,530	352.8	n.a.
1977	1,393	2,736	104,338	300.3	1,899
1978	1,586	2,979	128,635	388.9	2,144
1979	2,264	4,257	178,500	307.4	2,164
1980	1,111	2,103	100,940	297.6	3,119
1981	1,963	3,228	154,092	357.5	3,416
1982	2,071	3,578	169,453	330.1	2,617
1983	2,104	3,963	202,490	222.1	2,903
1984	2,606	4,481	204,125	353.4	2,970
1985	2,630	4,414	196,071	396	2,499
1986	2,334	3,985	212,143	365.9	2,158
1987	2,042	3,628	180,760	243	2,493
1988	2,771	4,564	241,000	439.9	3,612
1989	3,381	5,305	252,980	341.8	3,678
1990	2,124	5,244	260,600	382.4	3,952
Mean	2,029.6	3,680.7	171,185.4	346.3	2,758.9
S.D.	660.6	1,032.4	59,783.4	63.5	570.3

[a] Current farm price of rice in the dry season

APPENDIX D.

Discussion on Aggregation Techniques

The aggregation techniques employed in the present study are the Laspeyres index numbers and the Tornqvist (Divisia) index numbers. The Laspeyres indexes is one of the commonly and used aggregation techniques due to the ease in computations. The Laspeyres quantity index can simply be stated as

$$X^t/X^0 = \sum_{i=1}^{n} W_i^0 X_i^t / \sum_{i=1}^{n} W_i^0 X_i^0 \qquad (1)$$

where W_i^0 denotes the input price of the i^{th} input (i=1,...,n) in the base period (0). X_i^0 and X_i^t are the quantity of the input i at the base period (0) and the other period (t) respectively.

The Laspeyres index number (1) appears to be rather restrictive. The quantity aggregation over inputs can be exact if the ratios of aggregated quantity inputs are equal to the ratios of outputs produced from the given inputs during the same period. In other words,

$$X^t/X^0 = Y^t/Y^0 = f(X_1^t, ..X_n^t)/f(X_1^0, ..X_n^0) \qquad (2)$$

The relationship as specified in (2) has proved to hold true only when the technology employed in producing an output Y is characterized by either a linear or a fixed coefficients production function under static competitive profit maximizing or cost minimizing behaviour of the producer.

The Tornqvist quantity index using for aggregation a number of inputs in the production model can be written as

$$\log(X^t/X^0) = \sum_{i=1}^{n} S_i \log(X_i^t/X_i^0)$$
$$\text{where} \quad S_i = \frac{1}{2}\left(\frac{W_i^t X_i^t}{\sum_{i=1}^{n} W_i^t X_i^t} + \frac{W_i^0 X_i^0}{\sum_{i=1}^{n} W_i^0 X_i^0}\right) \tag{3}$$

The superscripts 0 and t denote the base period (0) and other period (t) whereas the subscript i represents the i^{th} input. S_i can be simply defined as the average of the shares of individual cost of input i in the base period (0) and the current period (t) considered in aggregation.

For the Tornqvist indexes, the relationship as specified in (2) has proved to hold true when assuming a constant return to scale Translog production function with cost minimizing behaviour. However, if profit maximization behaviour can be assumed, the Tornqvist indexes can be modified to represent an exact aggregation under a more flexible assumption of a variable return to scale Translog production function. The formula for the modified Tornqvist indexes can be presented as follows:

$$\log(X^t/X^0) = \sum_{i=1}^{n} S_i \log(X_i^t/X_i^0)$$
$$\text{where} \quad S_i = \frac{1}{2}\left(\frac{W_i^t X_i^t}{\sum_{j=1}^{m} P_j^t Y_j^t} + \frac{W_i^0 X_i^0}{\sum_{j=1}^{m} P_j^0 Y_j^0}\right) \tag{4}$$

From (4), Y represents outputs produced from a given set of inputs $(X_1,\ldots,X_n)$ and P denotes prices of outputs. The subscripts j refer to the j^{th} output where j=1,...,m. The superscripts 0 and t are defined as before.

Despite the rather stringent assumptions required to justify the best use of the aggregation analysis, both the Laspeyres and the Tornqvist indexes are attempted in the present study mainly to facilitate the estimation process. The disadvantages of inconsistencies in aggregation are traded off with the risks of model misspecification when one or more relevant variables has to be dropped out from the model due to multicollinearity problem. Besides, the primal interest of this study is the response of irrigation, other variables are of relatively less concern.

APPENDIX E.

Supplementary Table of Results: Farm Level Analysis

Table E.1 OLS Estimates for the Initial Specification of the Linear and Semilogarithmic Wet Season Rice Model (Equation (5.1))

Variable	Linear		Semilogarithmic	
	Estimate	T-ratio	Estimate	T-ratio
Constant	361.57	1.00	6.91	0.13
A	337.6	5.29***	0.11	4.95***
S	16.37	5.86***	0.55E-02	2.57***
F	2.07	1.50*	0.40E-03	0.83
Hi	0.78	1.71*	0.16E-03	1.01
Tr	31.26	3.54***	0.11E-01	3.75***
L	2.84	1.11	0.47E-03	0.53
DUM_H	11.48	0.06	0.44E-02	0.67E-01
DUM_O	-132.83	-0.32	0.11	0.73
A DUM_O	30.38	0.48	0.24E-01	1.10
Adjusted R^2	73.13		67.45	
Chi-square (Glejser test)	11.53		5.17	
D.W Statistic	2.15		2.18	

*** statistically significant at 99 percent
* statistically significant at 90 percent

Table E.2 Correlation Matrix of All Regressors Included in the Wet Season Rice Production: Farm Level Analysis

Variable	A	S	F	Tr	Hi	L	L1	L2	L3	L4	Lo	Lh	Le
A	1	0.7363	0.4789	0.7775	0.4889	0.7046	0.4691	0.3704	0.2518	0.6646	0.4632	0.6667	0.0271
S		1	0.2889	0.3966	0.1586	0.5204	0.3698	0.3010	0.2460	0.4370	0.3356	0.5110	0.0060
F			1	0.0226	0.4188	0.4918	0.1007	0.4488	0.8604	0.4914	0.0660	0.4103	0.0372
Tr				1	-0.1309	0.3281	0.1788	0.2667	0.3558	0.0278	0.1488	0.2258	0.1609
Hi					1	0.3276	0.0381	0.1954	0.8192	0.4914	0.0660	0.4103	0.0372
L						1	0.6231	0.7247	0.4516	0.8185	0.6334	0.6164	0.4088
L1							1	0.1105	0.3551	0.2162	0.8383	0.3559	-0.1041
L2								1	0.2579	0.5808	0.1803	0.3352	0.6586
L3									1	0.1031	0.4949	0.2807	-0.0009
L4										1	0.2764	0.5972	0.4486
Lo											1	0.2166	-0.0816
Lh												1	0.0961
Le													1

Table E.3 2SLS Estimates of the Linear Wet Season Rice Model (Equation (5.1))

Variable	Estimate	T-ratio
Constant	105.93	0.42
A	151.88	0.54
S	13.06	1.56
Tr	17.34	1.06
Hi	-0.12	-0.65E-01
L4	44.44	0.42
Adjusted R^2	63.26	
D.W.	1.94	

Table E.4 OLS Estimates for the Initial Specification of the Linear and Semilogarithmic Dry Season Garlic Model (Equation (5.4))

Variable	Linear		Semilogarithmic	
	Estimate	T-ratio	Estimate	T-ratio
Constant	110.54	0.35	7.03	18.06
A	455.62	1.86*	0.39	1.28
S	1.96	3.33***	0.15E-02	2.09*
F	0.46	0.37	0.23E-04	0.02
Hi	-0.55	-1.51	-0.39E-04	-0.09
L	8.07	2.65**	-0.51E-02	-1.35
DUM_O	-190.14	-0.52	-0.41	-0.89
A DUM_O	0.27	0.10E-02	0.13	0.45
Adjusted R^2	75.32		62.15	
Chi-square (Glejser test)	5.321		11.423	
D.W Statistic	2.04		2.31	

*** statistically significant at 99 percent
** statistically significant at 95 percent
* statistically significant at 90 percent

Table E.5 Correlation Matrix of All Regressors Included in the Dry Season Garlic Production: Farm Level Analysis

Variable	A	S	F	Hi	L	L1	L2	L3	L4	Lo	Lh
A	1	0.5705	0.5956	0.3634	0.8666	0.8439	0.7671	0.4585	0.8229	0.5495	0.8338
S		1	0.7366	0.5185	0.6226	0.5082	0.6242	0.6441	0.5078	0.7377	0.3318
F			1	0.6637	0.5311	0.4217	0.5840	0.6373	0.3836	0.4429	0.4283
Hi				1	0.3595	0.2529	0.3978	0.8330	0.1675	0.2685	0.3143
L					1	0.9178	0.9245	0.4845	0.9624	0.7613	0.8630
L1						1	0.7519	0.4077	0.8810	0.7764	0.7315
L2							1	0.4344	0.8469	0.6523	0.8380
L3								1	0.2906	0.4685	0.3405
L4									1	0.7032	0.8536
Lo										1	0.3295
Lh											1

Table E.6 Estimates of Dry Season Garlic Model Using Cobb-Douglas, Modified Translog and Modified Quadratic Functional Forms (Equations (5.4))

Variable	Cobb-Douglas		Modified Translog		Modified Quadratic	
	Estimate	T-ratio	Estimate	T-ratio	Estimate	T-ratio
Constant	5.37	15.04***	4.58	1.89**	62.94	0.35
A	-	-	-	-	267.53	1.21
S	-	-	-	-	3.30	1.98
L1	-	-	-	-	37.20	1.18
lnA	0.60	4.70***	0.50	1.87**	-	-
lnS	0.23	3.05***	0.59	0.79	-	-
lnL1	0.19	2.46**	0.49E-01	0.19	-	-
A^2	-	-	-	-	16.62	0.40
S^2	-	-	-	-	-0.17E-02	-0.66
$L1^2$	-	-	-	-	0.23	0.24
$(\ln A)^2$	-	-	0.48E-01	0.25	-	-
$(\ln S)^2$	-	-	-0.35E-01	-0.48	-	-
$(\ln L1)^2$	-	-	0.36E-01	0.48	-	-
Adjusted R^2	73.52		62.38		66.68	
Chi-square (Glejser test)	6.953		21.33		24.02	
D.W.	1.50		1.49		1.57	

*** statistically significant at 99 percent
** statistically significant at 95 percent

Table E.7 2SLS Estimates of Linear Dry Season Garlic Model (Equations (5.4))

Variable	Estimate	T-ratio
Constant	149.77	0.52
A	168.90	0.59
S	1.73	0.92
L1	87.16	1.23
Adjusted R^2	60.76	
D.W.	1.82	

Table E.8 OLS Estimates for the Initial Specification of the Linear and Semilogarithmic Inverted Transformation Model (Equation (5.6))

Variable	Linear		Semilogarithmic	
	Estimate	T-ratio	Estimate	T-ratio
Constant	0.41	1.00	-0.16	-0.76
Y1	0.34E-02	2.26**	0.22E-02	2.67**
Y2	0.20E-01	2.80**	0.12E-01	3.15***
Y3	0.33E-01	7.18***	0.13E-01	5.22***
Y4	0.26E-02	2.89**	0.14E-02	2.92**
F	-0.31E-02	-0.79	-0.25E-02	-1.18
Hi	0.68E-03	1.09	-0.72E-04	-0.22
L	0.19E-01	2.14**	0.75E-02	1.56*
Adjusted R^2	66.45		51.48	
Chi-square (Glejser test)	6.49		6.99	
D.W Statistic	1.97		2.36	

*** statistically significant at 99 percent
** statistically significant at 95 percent
* statistically significant at 90 percent

Table E.9 OLS Estimates of the Inverted Transformation Model Using Quadratic Functional Form Assuming disjoint Technology (Equation (5.6))

Variable	Estimate	T-ratio
Constant	0.25	0.35
Y1	0.11E-01	2.41**
Y2	0.53E-01	1.13
Y3	0.48E-01	2.63**
Y4	0.30E-02	0.77
L	0.81E-02	1.10
Y1*L	-0.97E-04	-0.58
Y2*L	-0.18E-03	-0.33
Y3*L	0.25E-03	0.68
Y4*L	0.57E-04	0.91
$Y1^2$	0.82E-06	0.59E-01
$Y2^2$	-0.24E-03	-0.48
$Y3^2$	-0.14E-03	-1.26
$Y4^2$	-0.29E-05	-0.59
L^2	0.14E-05	0.41
Adjusted R^2	67.10	
Chi-square (Glejser test)	31.24	
D.W.	2.34	

** statistically significant at 95 percent

Table E.10 2SLS Estimates for the Final Inverted Transformation Model (Equation (5.6))

Variable	Estimate	T-ratio
Constant	2.67	1.42
Y1	0.56E-02	0.95
Y2	0.20E-01	0.64
Y3	0.40E-01	2.75**
Y4	0.26E-03	0.87E-01
L	0.35E-01	0.50
Adjusted R^2	39.63	
D.W Statistic	1.99	

** statistically significant at 95 percent

APPENDIX F.

Supplementary Table of Results: National Level Analysis

Table F.1 ITSUR Estimates for the Wet Season Rice Model Using the Normalized Quadratic Specification (Equations (6.18)-(6.19))

Parameter	A		B		C	
	Estimate	T-Ratio	Estimate	T-Ratio	Estimate	T-Ratio
A1	1099349.17	1.19	1208836.73	1.73	2494761.87	3.25***
A11	-569001.57	-0.7	-635942.54	-0.91	-30582.03	-0.03
A13	-3580.21	2.09*	-3391.56	-2.52**	-4599.43	-2.66**
A3	-27040.94	-2.7**	-36956.53	-4.34***	-23883.84	-2.77**
A31	-4299.7	-0.49	1762.72	0.21	7916.8	0.79
A33	48.989	2.65**	31.904	1.95*	19.625	1.01
B11	18.271	0.26	13.851	0.22	-175.873	-5.34***
B12	-12.847	-1.9*	-13.176	-2.11*	-12.112	-1.45
B31	2.358	3.09**	2.758	3.56***	0.83	2.24**
B32	0.329	4.49***	0.359	4.72***	0.369	3.94***
C11	391.029	1.84*	381.148	1.94*	421.554	1.61
C12	-49572.56	-2.23*	-52371.1	-3.22***	-	-
C31	3.384	1.47	4.279	1.79	4.689	1.59
C32	-785.85	-3.26***	-532.403	-2.7**	-	-
D11	-0.451	-0.19	-	-	-	-
D31	0.041	1.63	-	-	-	-
Equation	D.W Statistic	Adjusted R^2	D.W Statistic	Adjusted R^2	D.W Statistic	Adjusted R^2
F	2.07	88.93	2.051	89.90	1.059	81.99
Y	2.345	87.18	2.388	85.25	2.269	77.55

A Initial specification where tractor and time variables were included.
B Tractor was excluded.
C Tractor and time variables were omitted.
*** statistically significant at 99 percent
** statistically significant at 95 percent
* statistically significant at 90 percent

Table F.2 IT3SLS Estimates for the Wet Season Rice Model Using the Normalized Quadratic Specification (Equations (6.18)-(6.19))

Parameter	A		B	
	Estimate	T-Ratio	Estimate	T-Ratio
A1	1364222	1.13	1182869.68	0.87
A11	-1060101	-1.03	28800.78	0.03
A13	-3326.08	-1.86*	-5656.96	-3.34***
A3	-15177.4	-1.09	-17734.02	-1.00
A31	-13085.9	-1.10	2265.21	0.17
A33	50.923	2.45**	18.063	0.82
B11	29.481	0.36	-55.849	-0.67
B12	-18.65	-1.85*	-13.09	-1.18
B31	1.82	1.91*	0.617	0.56
B32	0.221	1.89*	0.3	2.07*
C11	469.706	1.94*	540.955	2.00*
C12	-56756.1	-2.38**	-	-
C31	4.837	1.73	5.841	1.65
C32	-800.135	-2.89*	-	-
D11	-0.153	-0.06	-3.826	-1.69
D31	0.053	1.82*	0.002	0.06
Variable	D.W Statistic	Adjusted R^2	D.W Statistic	Adjusted R^2
F	2.313	88.01	1.639	84.69
Y	2.266	84.13	2.253	74.20

A Initial specification where tractor and time variables were included.
B Time variable was excluded.
*** statistically significant at 99 percent
** statistically significant at 95 percent
* statistically significant at 90 percent

Table F.3 ITSUR Estimates for the Initial Specification of the Wet Season Rice Model Using the Generalized Leontief Form (Equations (6.21)-(6.23))

Parameter	All Coefficients		Symmetry Restrictions Imposed	
	Estimate	T-Ratio	Estimate	T-Ratio
A1	382174.07	0.47	402994.32	0.52
A12	204526.98	2.07*	-	-
A13	-28689.49	-3.15**	-28545.86	-3.32***
A2	-255785.63	-0.23	425568.25	0.51
A21	784189.10	1.05	212138.69	2.30**
A23	-26331.39	-0.86	-27342.33	-1.87*
A3	-25136.92	-2.17*	-19267.89	-2.08*
A31	35986.54	0.46	-	-
A32	-48581.86	-1.98*	-	-
B11	2.517	0.03	1.300	0.02
B12	-1.939	-0.39	-2.203	-0.47
B21	-43.742	-0.57	-60.131	-0.83
B22	-5.293	-0.76	-10.272	-2.25**
B31	2.698	2.99**	2.456	2.84**
B32	0.318	4.74***	0.277	5.48***
C11	190.815	1.02	191.155	1.07
C12	-30564.43	-1.31	-31404.69	-1.41
C21	-61.864	-0.28	25.732	0.13
C22	2342.51	0.10	-1514.37	-0.08
C31	4.458	1.94*	4.959	2.21**
C32	-721.197	-2.60**	-764.899	-3.15***
D11	-2.122	-0.94	-2.104	-0.98
D21	4.971	2.04*	5.076	2.45**
D31	0.029	1.12	0.030	1.21
Equation	D.W Statistic	Adjusted R^2	D.W Statistic	Adjusted R^2
F	2.014	88.85	2.024	89.86
L	2.439	83.82	2.264	84.43
Y	2.367	84.05	2.199	84.25

*** statistically significant at 99 percent
** statistically significant at 95 percent
* statistically significant at 90 percent

Table F.4 IT3SLS Estimates for the Initial Specification of the Wet Season Rice Model Using the Generalized Leontief Form (Equations (6.21)-(6.23))

Parameter	All Coefficient		Symmetry Restriction Imposed	
	Estimate	T-Ratio	Estimate	T-Ratio
A1	24914.21	0.03	121040.44	0.14
A12	153676.57	1.40	-	-
A13	-28175.43	-2.94**	-28044.30	-3.13***
A2	-649548.31	-0.48	543019.09	0.60
A21	1355682.62	1.52	181307.66	1.79
A23	-43328.31	-1.25	-23855.91	-1.52
A3	-9339.98	-0.64	-11102.27	-1.07*
A31	-47106.68	-0.48	-	-
A32	-21993.81	-0.74	-	-
B11	31.145	0.38	24.930	0.32
B12	0.572	0.09	-0.518	-0.09
B21	-56.854	-0.63	-78.367	-0.99
B22	1.025	0.11	8.998	1.74
B31	1.718	1.56	1.706	1.72
B32	0.226	2.41**	0.238	3.97***
C11	179.663	0.94	183.465	1.02
C12	-30080.41	-1.22	-32276.16	-1.39
C21	-109.382	-0.46	7.145	0.04
C22	15191.70	0.55	14.529	0.00
C31	5.213	1.99*	5.197	2.18*
C32	-691.598	-2.12*	-648.081	-2.44**
D11	-2.374	-1.01	-2.326	-1.06
D21	4.083	1.52	5.385	2.55**
D31	0.042	1.40	0.039	1.49
Equation	D.W Statistic	Adjusted R^2	D.W Statistic	Adjusted R^2
F	2.114	88.32	2.121	89.69
L	2.599	81.72	2.357	84.25
Y	2.333	79.82	2.383	82.26

*** statistically significant at 99 percent
** statistically significant at 95 percent
* statistically significant at 90 percent

Table F.5 ITSUR Estimates for the Wet Season Normalized Quadratic Dual Model: Estimation of Profit Equation in Simultaneously with the System of Input Demand and Output Supply Equations[1] (Equations (6.17)-(6.19))

Parameter	Estimate	T-Ratio
A1	935634.04	1.35
A11	248180.79	0.41
A13	-3681.46	-2.82**
A3	-38635.88	-4.69***
A33	37.137	2.34**
B11	27.304	0.43
B12	-5.513	-1.03
B31	3.027	3.99***
B32	0.412	6.57***
C11	-51764.07	-3.16**
C31	-579.187	-2.97**
α0	25064892	0.20
α3	-3941.53	-0.15
α4	-745.136	-0.41
α6	2055760.11	0.34
ß10	0.043	0.18
ß12	-142.887	-0.18
ß14	-22.7	-0.35
δ3	0.182	0.11
δ4	0.005	0.91
δ6	25374.67	0.27
Equation	**D.W Statistic**	**Adjusted R^2**
F	1.391	-
L	1.920	89.57
Y	2.137	85.42

[1] Explanatory variables include prices, irrigated rice area, total rice area, and time trend. Note that when the time trend was replaced with other variables such as rainfall or tractors, convergence was not obtained.

*** statistically significant at 99 percent
** statistically significant at 95 percent
* statistically significant at 90 percent

Table F.6 ITSUR and IT3SLS Estimates for the Wet Season Rice Model Using the Normalized Quadratic Functional Form (Fertilizer Input Price As a Numeraire)[1]

Parameter	ITSUR[a]		IT3SLS[b]	
	Estimate	T-Ratio	Estimate	T-Ratio
A2	-1091531.72	-1.25	-157553.28	-0.16
A22	7494.33	0.38	-4059.31	-0.23
A23	-347.67	-1.74	-99.62	-0.46
A3	-34328.08	-4.16***	-17403.29	-1.63
A32	-320.52	-1.73	-333.09	-1.66
A33	3.19	1.68	5.06	2.11*
B21	-0.77	-0.01	-26.15	-0.31
B22	-5.46	-1.01	-6.58	-1.14
B31	2.83	3.35***	1.93	2.05*
B32	0.28	5.49***	0.21	3.32***
C21	127.38	0.56	-8.86	-0.04
C22	31491.16	1.30	-7047.09	-0.24
C31	6.77	3.12***	5.88	2.55**
C32	-458.12	-2.00**	-693.82	-2.15*
D21	-	-	5.44	2.08*
D31	-	-	0.05	1.78
Equation	D.W Statistic	Adjusted R^2	D.W Statistic	Adjusted R^2
L_d	1.697	76.54	2.382	82.46
Y_d	2.439	83.83	2.452	83.29

[1] The estimating equations are specified as follows:

$$L = -(A_2+A_{22}(W_2/W_1)+A_{23}(P/W_1)+B_{21}Ia +B_{22}Ta+C_{21}R+C_{22}T+D_{21}Tr)$$

$$Y = A_3+A_{32}(W_2/W_1)+A_{33}(P/W_1)+B_{31}Ia +B_{32}Ta+C_{31}R+C_{32}T+D_{31}Tr$$

a, b Reciprocity conditions were not further imposed due to the insignificant cross price effects (A23 and A32).
*** statistically significant at 99 percent
** statistically significant at 95 percent
* statistically significant at 90 percent

Table F.7 Estimates of Dry Season Rice Production Function Using the Cobb-Douglas Functional Form (Initial Specification: Equation (6.13))

Variable	Estimate	T-ratio
Constant	-114.76	-1.35
lnF_d	-0.40	-0.56
$lnIa_d$	1.38	2.12*
lnDRM	0.10	0.58
lnL_d	7.08	1.30
lnTr	-0.09	-0.37
Tt	-0.08	-1.67
Adjusted R^2	89.19	
D.W. Statistic	1.720	

* statistically significant at 90 percent

Table F.8 Correlation Matrix of All Regressors Included in the Dry Season Primal Analysis (1975-90)

Variable	Ia_d	F_d	L_d	DERM	Tr	Tt	Ry
Ia_d	1	0.9674	0.4262	0.0211	0.8313	0.8524	0.2095
F_d		1	0.2324	-0.0202	0.9141	0.9295	0.2409
L_d			1	0.1132	-0.0344	-0.0168	-0.1778
DERM				1	-0.0822	-0.0356	0.377
Tr					1	0.9733	0.376
Tt						1	0.3233
Ry							1

Table F.9 Estimates of Dry Season Rice Production Function Using the Modified Quadratic and Translog Functional Forms[1] (Equation (6.13))

Quadratic			Translog		
Variable	Estimate	T-ratio	Variable	Estimate	T-ratio
Constant	-4672.95	-0.67	Constant	-180.14	-0.51
DRM	10.08	0.46	lnDRM	9.35	0.57
Ia_d	-1.74	-0.63	$lnIa_d$	2.08	0.10
L_d	0.19	0.73	lnL_d	26.03	0.36
FTr	1250.90	1.25	lnFTr	0.50	1.31
$(DRM)^2$	-0.02	-0.46	$(lnDRM)^2$	-0.81	-0.57
$(Ia_d)^2$	0.01E-02	0.54	$(lnIa_d)^2$	-0.17	-0.14
$(L_d)^2$	-0.08E-05	-0.55	$(lnL_d)^2$	-1.09	-0.33
$(FTr)^2$	1009.42	0.74	$(lnFTr)^2$	0.37	0.74
Adjusted R^2	49.36		Adjusted R^2	70.21	
D.W. Statistic	2.140		D.W. Statistic	2.185	

[1] Specification were without interactive terms

Table F.10 Estimates of Dry Season Rice Yield Model Using Linear and Cobb-Douglas Functional Forms

Linear			Cobb-Douglas		
Variable	Estimate	T-ratio	Variable	Estimate	T-ratio
Constant	0.315	0.55	Constant	-8.136	-1.60
DRM	0.428	0.62	lnDRM	0.513	1.25
AF_d	0.004	0.54	$lnAF_d$	0.697	1.14
Ia_d	0.392E-04	0.71	$lnIa_d$	0.385	1.39
AL_d	0.002	0.20	$lnAL_d$	0.522	1.01
ATr	0.003	0.63	lnATr	0.141	0.87
Tt	-0.010	-0.72	Tt	-0.012	-0.58
D.W. Statistic	1.882		D.W. Statistic	2.079	

Table F.11 ITSUR and IT3SLS Estimates for the Dry Season Rice Model Using the Normalized Quadratic Form (Fertilizer Input Price As a Numeraire)[(1)]

Parameter	ITSUR[a]		IT3SLS[b]	
	Estimate	T-Ratio	Estimate	T-Ratio
A2	-43749.03	-4.91***	-46559.40	-4.91***
A22	823.91	0.51	911.64	0.55
A23	-3.56	-0.19	-8.27	-0.42
A3	-46.63	-0.12	-85.21	-0.21
A32	-11.04	-0.16	-9.84	-0.14
A33	0.02	0.02	-0.04	-0.05
B21	-15.62	-4.64***	-12.99	-3.14***
B31	0.53	3.58***	0.57	3.18***
D21	0.23	1.54	0.18	1.12
D31	0.25E-02	0.38	0.18E-02	0.26
Equation	D.W Statistic	Adjusted R^2	D.W Statistic	Adjusted R^2
L_d	1.843	58.20	2.059	55.89
Y_d	1.769	79.02	1.727	78.91

[(1)] The estimating equations are specified as follows:

$$L_d = -(A_2+A_{22}(W_2/W_1)+A_{23}(P_d/W_1)+B_{21}Ia_d +C_{21}R+C_{22}T+D_{21}Tr)$$

$$Y_d = A_3+A_{32}(W_2/W_1)+A_{33}(P_d/W_1)+B_{31}Ia_d +C_{31}R+C_{32}T+D_{31}Tr$$

a, b Reciprocity conditions were not further imposed due to the insignificant cross price effects (A23 and A32).

*** statistically significant at 99 percent