DISSERTATION

SOIL DEGRADATION IN CHINA: IMPLICATIONS FOR AGRICULTURAL SUSTAINABILITY, FOOD SECURITY AND THE ENVIRONMENT

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In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

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Fall 2012

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UMI 3551622

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ABSTRACT

SOIL DEGRADATION IN CHINA: IMPLICATIONS FOR AGRICULTURAL SUSTAINABILITY, FOOD SECURITY AND THE ENVIRONMENT

This dissertation consists of one introduction chapter and three essays, which describe and discuss methods to address three separate but related issues in soil management in China. In my introductory Chapter, I discuss the background for the soil degradation in China and how soil degradation threatens food security, the environment and agricultural sustainability.

In the first essay in Chapter 2, I develop a dynamic optimization model for soil management and provide implications for the influence of externalities on intertemporal management of soil capital. This chapter contributes to the literature by providing a more comprehensive dynamic optimization model from a social planner's standpoint, who is concerned about agricultural sustainability, environmental quality and food security. A comparison by numerical methods between a public model and a private model implies that optimal soil management path is different for farmers than for social planners when externalities are considered. This implies that it is important to take externalities into account when managing natural capital such as soil. Food security, as a positive externality, and environmental pollution, as a negative externality, are complementing each other. Factors affecting farm profits and externalities also affect the optimal path.

In Chapter 3, I propose environment-adjusted profit as a more appropriate tool to measure the costs imposed by environmental regulations than abatement costs from a shadow pricing model. Environment-adjusted profit updates abatement costs by taking farmers' mitigation behavior into account. Both abatement costs and environment-adjusted profit are estimated for over 1,700cropping systems in the Loess Plateau of China. Furthermore, a regression was used to determine the cropping systems that are most profitable as environmental regulations were imposed. Results show that conservation techniques and mono-crop corn and rotations such as corn-soybean-corn and alfalfa 3 years-corn-millet contribute more to farm profit if environmental regulations were imposed. The conclusions from this chapter can provide farmers and policy-makers alternative choices to balance both economic and environmental goals, rather than planting all land to trees through the Grain for Green program, which was the choice for many in the Loess Plateau.

In Chapter 4, I update the sustainable value approach by a DEA benchmark and apply it to the cropping systems in the Loess Plateau of China to investigate sustainable value and efficiency as measures of sustainability. The cropping systems that contribute the most to sustainability from the perspective of using all types of capital efficiently are identified by a regression model. Sustainable value and efficiency matrices are created to compare the sustainability between any pair of rotations and conservation techniques. Rotations such as CSC, A3CM and FA5MC are most sustainable. Conservation techniques such as terracing, mulching and furrow-ridging are more sustainable. This chapter contributes the literature in soil science by adding economic perspective in analyzing agronomic techniques.

TABLE OF CONTENTS

CHAPTER 1 OVERVIEW 1
1.1 Background 1
1.1.1 Soil Degradation in China 2
1.1.2 Food Security and Soil Degradation 3
1.1.3 The Environment and Soil Degradation 5
1.1.4 China's Conservation Programs 7
1.1.5 Agricultural Sustainability 8
1.2 Broad Objectives 9
1.3 Literature Review 11
1.3.1 Productivity Impacts and On-site Economic Costs 11
1.3.2 A Threat to Food Security 13
1.3.3 Off-site Economic Costs 14
1.3.4 Incentives to Control 15
1.3.5 A Threat to Agricultural Sustainability 19
1.4 Dissertation Organization 20
CHAPTER 2 21
THE INFLUENCE OF EXTERNALITIES ON INTERTEMPORAL MANAGEMENT OF SOIL CAPITAL: A DYNAMIC PROGRAMMING APPROACH 21
2.1 Introduction 21
2.2 Externalities and Soil Management 25
2.2.1 Food Security and Sustainable Soil Management 25
2.2.2 Environmental Pollution and Sustainable Soil Management 28
2.3 Model Description and Optimization Technique 29
2.3.1 Soil Properties and Soil Erosion 30
2.3.2 Crop Production and Profit 32
2.3.3 Environmental Pollution 33
2.3.4 Food Security 33
2.3.5 Private Model 35
2.3.6 Public Model 35
2.3.7 Optimization Technique: The Bellman Equation 36
2.4 An Empirical Example 38
2.4.1 Model Parameters 38
2.4.2 Optimal Solutions 41
2.5 Discussion and Conclusions 46
CHAPTER 3 49
SHADOW PRICING ABATEMENT COSTS OF AGRICULTURAL POLLUTANTS IN THE LOESS PLATEAU OF CHINA 49
3.1 Introduction 49
3.2 Methodology 53
3.2.1 Shadow Pricing Model and Its Estimation 53
3.2.2 Contribution of Crop Management Alternatives 62
3.3 Data 65

3.4 Empirical Results 68
  3.4.1 Distance Function Values and Shadow Prices 68
  3.4.2 Marginal and Total Abatement Costs 72
  3.4.3 Contribution of Cropping Practice Alternatives 76
3.5 Conclusion and Discussion 82
CHATPTER 4 85
SUSTAINABLE VALUE AND EFFICIENCY OF CROPPING SYSTEMS IN THE LOESS PLATEAU OF CHINA 85
4.1 Introduction 85
4.2 Methodology 89
  4.2.1 The Sustainable Value Approach 89
  4.2.2 Steps to Calculate Sustainable Value and Efficiency 93
  4.2.3 DEA Method to Formulate the Benchmark 95
  4.2.3 Contribution of Conservation Practice Alternatives 98
4.3 Data 99
4.4 Empirical Results 102
  4.4.1 DEA Benchmarks 102
  4.4.2 Sustainable Value and Sustainable Efficiency 103
  4.4.3 Robustness of the DEA Benchmarks 105
  4.4.4 Contribution of Conservation Alternatives 106
4.5 Conclusions and Discussions 115
REFERENCES 119
APPENDIX 1 125
APPENDIX 2 133
APPENDIX 3 136

CHAPTER 1

OVERVIEW

1.1 Background

Food security is a great challenge for China with 7% of the world's total arable land feeding over one-fifth of the world's total population. China's agricultural sector has succeeded in providing food and fiber products to its people, and enhancing the nation's food security in the past few decades. Institutional reforms, technology progress and intensified agricultural inputs all contributed to these achievements. However, some efforts have been criticized for being made at the cost of environmental and resource deterioration. Soil degradation, for example, decreases crop yields and thus financial returns to agricultural production, thereby threatening food security, environmental quality and agricultural sustainability.

In this chapter, I discuss how soil degradation threatens farm profits and produces positive and negative externalities such as food security and water contamination, respectively. This discussion provides a background for my three essays that follow this chapter, especially for those less familiar with soil erosion and conservation issues in China.

1.1.1 Soil Degradation in China

The Assessment of the Status of human-induced Soil Degradation in South and Southeast Asia (ASSOD[1]) project developed a 1:5 million map of soil degradation in South and Southeast Asia based on the Soils and Terrain Digital Database (SOTER). IIASA's LUC Project analyzed the ASSOD database specifically for China. As is shown in Table 1.1, more than 466 million hectares (ha) (or 50% of the land) in China is affected by one type of soil degradation or another, 73 million ha by moderate degradation and 86 million ha by strong soil degradation. Over 60% of the cultivated land is affected by some kind of moderate or strong soil degradation (Heilig, 2004). There is no doubt that soil degradation is one of the most serious agricultural and environmental problems in China.

Table 1.1. Soil Degradation in China According to ASSOD Assessment (in million hectares)

Types	Subtypes	Negligible	Light	Moderate	Strong	Extreme
Water Erosion	Loss of Topsoil	15.8	105.9	44.9	3.8	0.2
	Terrain Deformation	0.5	7.9	5.9	24.0	-
	Off-site Effects	0.2	0.2	0.2	-	-
Wind Erosion	Loss of Topsoil	1.7	65.9	2.5	+	+
	Terrain Deformation	+	7.2	5.5	57.9	-
	Off-site Effects	+	2.0	6.5	0.2	-
Chemical Deterioration	Fertility Decline	32.4	31.7	4.8	-	-
	Salinisation	0.5	6.8	2.6	-	-
	Dystrification	-	+	-	-	-
Physical Deterioration	Aridification	-	23.7	-	-	-
	Compaction and Crusting	-	0.5	-	-	-
	Waterlogging	3.8	-	-	-	-
Total Degradation	All Types	55.0	251.9	72.9	86.0	0.25

Source: Van Lynden and Oldeman (1997)

Note: (-) no significant occurrence; (+) Less than 0.1 but more than 0.01 million hectares; for calculation of the totals we have assumed that (+) is equivalent to 0.05 million hectares.

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[1] For more details on ASSOD database, see Van Lynden and Oldeman (1997).

The Loess Plateau in China, as one of the most severely degraded areas in the world, has over 60% of the land subject to soil degradation, with an average annual soil loss of 2000-2500 t/km^2 (Shi and Shao, 2000). Soil degradation due to human activities is usually called accelerated degradation, which arises from cultivation, uncontrolled development, overgrazing, mining, road construction and other human activities. Cultivation of marginal slope land is the major factor for the severe soil degradation for the Loess Plateau area (Lu *et al.*, 2003).

1.1.2 Food Security and Soil Degradation

China has made some achievements in fighting food insecurity in the past few decades. For example, food supplies have increased from 1470 to 2980 kcal/capita/day, protein from 40 to 89 g/capita/day, and fat from 16 to 92 g/capita/day from 1960 to 2007 (Food Balance Sheet, FAOSTAT, 2011). The net per capita production index for food increased from 27 in 1961 to 113 in 2009, based on period 2004-06 (Production Indices, FAOSTAT, 2009). Meantime, the national poverty rate decreased from 6.0% in 1996 to 2.8% in 2004 (World Bank, 2011).

However, policy makers and government officials are increasingly concerned about whether China can sustain food security for the future generation. An enormous population, fast urban expansion and income growth all threaten food security. The population size is projected to peak at 1.45 billion in 2030[2]. The percentage of population residing in urban areas is projected to be 60% in 2030 and 73% in 2050[3]. At the same time, limited arable land and water resources are

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[2] United Nations. 2004. World Population to 2300. New York

[3] United Nations. 2007. World Urbanization Prospects: The 2007 Revision.New York

being shifted to non-agricultural sectors (Liao, 2010). Cropland has been lost at a rate of 1.45Mha/yr since 2000 (Ye and Ranst, 2009). Thus, soil productivity on land remaining in production becomes increasingly more critical to preserve. However, soil degradation threatens food security by undermining agricultural productivity, or in other words, lowering crop yields and increasing the need for substituting inputs like fertilizer and lime. This is usually called "on-site" effects. Food deficits were predicted to be 3-5%, 14-18% and 22-32% by 2030-2050 under the zero-degradation, the current degradation rate and double-degradation rate scenarios, respectively (Ye and Ranst, 2009).

In an effort to meet the increasing food demand in the current period, which is driven by population growth, urbanization and income growth, the soil capital has been overexploited, resulting in severe soil degradation and thinner soil layers for the future. This means, food security in the present is achieved by sacrificing food security in the future by overexploiting the soil capital. Several researchable questions arise, such as: How to allocate soil capital intertemporally in an efficient and sustainable way? How to sustain a program to accomplish food security in the present without sacrificing food security in the future by controlling soil degradation? Where will tradeoffs be most severe? And how soil degradation, technology innovation and other management or policy decisions affect food security?

1.1.3 The Environment and Soil Degradation

As pointed about thirty years ago by Clark et al. (1985), the erosion and runoff processes create a set of potential pollutants including the resulting sediments and associated substances. These pollutants are transported into and through waterways, where they can directly or indirectly cause certain effects. These effects, in turn, directly or indirectly create various costs (or benefits) for society. Thus, environmental effects are often referred to as “off-site” effects, such as air and water pollution, degraded recreation services, damages to wildlife diversity, flood damages, and siltation in water conveyance. Table 1.2 summarizes the types of degradation impacts and their processes.

Table 1.2. Environmental Impacts from Soil Degradation and Their Process

Type of Impacts	Impact process
In-stream effects	
Biological	Turbidity and sedimentation cause damage either directly, through physically or biologically affecting aquatic organism itself, or indirectly, through destroying the organism’s required habitat.
Recreational	High turbidity probably reduces the pleasure of swimming and boating; Turbidity and sedimentation can significantly decrease the quality of sports fishing; can diminish the quality of the recreational experience.
Water-storage facilities	Reduce lakes and reservoirs’ water-storage capacity, changing the temperature of the water, and providing increased opportunities for the growth of water-consuming plants.
Navigation	The sedimentation occurring in harbors, bays, and navigation channels reduces the capacity of these facilities to handle commercial and recreational craft, increases the likelihood of shipping accidents, and requires expensive dredging to keep the facilities usable.
Other in-stream uses	Hydroelectric and other machinery that operates in water
Off-stream effects	
Flood damages	In any stretch where a streambed has aggraded, the elevation of the water surface associated with any volume of flow will be higher and may flood adjacent land in the absence of what would otherwise be a flood flow.
Water-Conveyance facilities	Sedimentation will require increased maintenance efforts to remove sedimentation; high turbidity can increase the cost of pumping water from its source.

Water-treatment facilities	Both the investment and the operation and maintenance costs of the water-treatment facility will increase as the turbidity of a water supply increases.
Other off-steam uses	Suspended sediment in irrigation water can form a crust on a field, reducing the amount of water that seeps into the soil, inhibiting the emergence of plants, and preventing adequate soil aeration. Sediment may also coat the leaves of young plants.

Source: adapted from Clark et al. (1985)

Flood damage in the lower reaches of Yellow River is one of the most serious off-site effects caused by the sediment from soil degradation in the Loess Plateau. The riverbed of the lower reaches has been raised at an annual rate of 8-10 cm by sedimentation (Shi and Shao, 2000). However, rational farmers in the upper reaches will not internalize these negative externalities based on their decision-making rules even though various control techniques are available for them, such as tillage practices, cropping patterns, structural measures and other land management practices[4]. This means that the private optimal level of degradation control must be lower than the social optimality due to the negative externalities. Thus, the questions arise. What are the social and private optimal levels of degradation control? What kind of conservation programs need to be designed and implemented by the government to provide enough incentives for farmers to meet the social optimal control level? What are the costs and benefits from these conservation programs? What factors affect farmers' decisions to adopt conservation practices?

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[4] For more detailed information on the relevant aspects of these different techniques such as costs ,effectiveness and ancillary effects, see Clark et al. (1985). For more information about China's conservation system, see Gao, W.S., 2010. Conservation Farming System in China. China Agricultural University Press, Beijing.(in Chinese).

1.1.4 China's Conservation Programs

Facing serious soil degradation and its associated ecological and environmental problems, the Chinese government formally implemented six key State Forestry development programs including the Natural Forest Protection Program (NFPP), Key Shelterbelt Construction Program, Grain for Green Project (GGP), the desertification control program, the conservation of biodiversity and nature conservation construction program, and the establishment of the fast-growing and high-yielding timber plantation (Li, 2004). Besides these, farmers are also subsidized to employ conservation practices by the agricultural technology subsidy. A program called Proper Fertilization by Soil Testing (PFST) is implemented to educate farmers on efficient fertilization.

Among these programs, Grain for Green Project (GGP) is the largest in terms of its ambitious goals, massive scales, huge payments, and potentially enormous impacts (Liu *et al.*, 2008). The GGP began its pilot study in Sichuan, Shanxi and Gansu provinces in 1999 and finally covered 25 of all 30 provinces. It aims to increase vegetative cover by 32 million ha by 2010, of which 14.7 million ha will be converted from cropland on steep slopes[5] back to forest and grassland; the remaining cover will be created on barren land. Under the GGP, the government offers farmers 2,250 and 1,500 kg of grain (or 3,150 and 2,100 yuan at 1.4 yuan per kg of grain) per ha of converted cropland per year in the upper reach of the Yangtze River Basin and in the upper and middle reaches of the Yellow River Basin, respectively. In addition, 300

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[5] Steep slope means the steepness over 15° for the northwestern China, and over 25° elsewhere.

yuan/ha per year for miscellaneous expenses and a one-time subsidy of 750 yuan/ha for tree seeds or seedlings are provided (Liu *et al.*, 2008). A two-year subsidy will be paid if the cropland is converted into grassland, five years if converted into economic forests by using fruit trees, or eight years if converted to ecological forests. By the end of 2005, over 90 billion yuan (about 14 billion US dollars) had been invested and the planned total investment will reach 220 billion yuan (about 35 billion US dollars) (Liu *et al.*, 2008).

The national forest coverage reached 30% in 2007, increased by 10% compared to 1998. The data from the sampled counties[6], monitored by the National Forestry Bureau, shows that the ratio between the cultivated slope land over 25 degrees and total cultivation decreased from 19.75% to 13.25%. The area suffering from soil and water loss decreased by about 20% from 1998 to 2006 in these sampled counties. There is a 29% decrease in the income from cropping, a 2% increase in the livestock industry and a 12% increase for migrant workers from 1998 to 2007. Crop production was reduced by 13.4% during the same period. However, GGP had only a small effect on China's grain production and almost no effect on prices or food imports by the simulation model from Xu et al. (2006).

1.1.5 Agricultural Sustainability

Concerns on the impacts of food security and environmental quality from soil degradation are related to the concept of "agricultural sustainability". As pointed out by Pretty (2008),

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[6] Sample data from "The evaluation report of social and economic benefits of the national key forestry programs 2008"

“Concerns about sustainability in agricultural systems centre on the need to develop technologies and practices that do not have adverse effects on environmental goods and services, are accessible to and effective for farmers, and lead to improvements in food productivity.” Resilience (i.e. the capacity of agricultural systems to buffer shocks and stress) and persistence (i.e. the capacity of agricultural systems to continue over long periods) are the two key characteristics of agricultural sustainability. The sustainability of the Chinese agricultural sector has been challenged by the environmental changes such as soil degradation and its associated detrimental effects. Thus, questions arise. Can China make its agricultural systems sustainable under ecological, economic and social pressures? How should China’s government respond to these environmental changes?

1.2 Broad Objectives

To meet the food demand driven by the population growth, urbanization expansion and income growth, the natural resources have been overexploited, thus resulting in vulnerable agricultural systems. The capacities of the systems to provide agricultural and ecological services in the future have been challenged by the associated environmental degradation and resource deterioration. This is a spiral of unsustainability. The relationships between soil degradation, food security and environmental quality set an example. Soil degradation that is exacerbated to meet food security in the current period will threaten food security in the future. In other words, the food security in the future is sacrificed to meet the food security in the present by the intensified agricultural practices. Furthermore, soil degradation generates many kinds of negative effects to the environment.

The broad objective of my dissertation is to develop approaches and methods to study the effects of soil degradation on food security, the environment and agricultural sustainability, and to understand how conservation practices change these effects. The Loess Plateau is an excellent case study of conflict between private and public objectives and therefore an appropriate place to demonstrate and investigate the methods and approaches developed in my dissertation. However, my data is insufficient to make specific recommendations for that region. I will pursue my broad objective through three journal-ready essays, each addressing one of the following more specific objectives:

- To develop a more comprehensive dynamic optimization model for soil management that account for positive externalities, such as food security, and negative externalities, such as environmental pollution; and to offer some implications about the influence of the externalities on intertemporal soil management. The optimization model is used to provide a formal framework for studying soil degradation.
- Environment-adjusted profit is defined to measure the cost imposed by environmental regulations, based on the abatement costs to prevent soil degradation;
- Cropping systems are identified that can sustain agricultural development in the Loess Plateau of China, by taking natural capital into account together with social and human capital.

1.3 Literature Review

1.3.1 Productivity Impacts and On-site Economic Costs

The fact that soil degradation decreases crop yield and thus returns to agricultural production by reducing agricultural productivity has long been recognized by agronomists and soil scientists (Pierce *et al.*, 1984; Alt *et al.*, 1989; Lal, 1995; Hopkins, 2001; Den Biggelaar *et al.*, 2003). The Pierce Index, developed by Neill[7] and modified by Pierce et al. (1983), is the common tool to quantify soil productivity. The model is represented by $PI = \sum_{i=1}^{r}(A_i \cdot C_i \cdot D_i \cdot WF)$, where A is the sufficiency of available water capacity, C is the sufficiency of bulk density, D is the sufficiency of pH, WF is a weighting factor representing an idealized rooting distribution, and **r** is the number of horizons in the rooting depth. Li *et al.* (2002) extend this method to Analytical Hierarchy Process (AHP) method and applied it to Chunhua County on the Loess Plateau in China. The AHP method has the advantage of accounting for more factors such as socio economic factors into the evaluation system by using different hierarchies and dimensions. Duan *et al.* applied this method to the black soil region in China (2011). But, as pointed by Lal (1995), PI values are not strongly correlated with the observed crop yield. Jaenicke and Lengnick (1999) criticized the PI value for requiring individual properties to be weighted subjectively without statistical tests. They also proposed a soil quality index (SQI) by a distance function approach

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[7] Neill, L. L. 1979. An evaluation of soil productivity based on root growth and water depletion. M.S. thesis. Univ. Mo., Columbia.

based on Fare et al. (1996). This SQI can account for technical efficiency and agricultural productivity.

The productivity change method and the replacement costs method are the two methods commonly used by economists to estimate the on-site costs from erosion. The productivity change method first estimates the relationship between topsoil depth and yield. It assumes that optimal adoption of soil conservation measures reduces soil erosion back to zero, which leads to an overestimation of on-site costs. It also ignores the offset effects from the technological improvement (Walker and Young, 1986), which will underestimate the on-site costs. Bishop *et al.* (1989) applied this method to the cultivated land within a north-south swath of Mali, and concluded that the net farm income foregone nationwide due to soil erosion is estimated at US$ 4.6 to $18.7 million.

The replacement cost method assumes that the productivity of soil can be maintained if the lost nutrients and organic matters are replaced artificially (Gunatilake and Vieth, 2000). Cruz *et al.,* (1988) applied replacement costs method to the Magat and Pantabangan watersheds in the Philippine. They conclude that the loss is about 3,392 Philippine peso in Magat and 1,411-2,541 Philippines pesos in Pantabangan. Riksen and Graaff (2001) applied this method to on-site costs of wind erosion. In this case, economic costs included decreased soil productivity, additional labors, replacement costs of agrochemicals, plants and seeds, loss of production, and repair and maintenance cost. Their results show that on-site costs vary across different crops. The average annual on-site cost in high-risk areas amounts to about €60 per hectare. However, for sugar beet and oilseed rape the costs can be as much as €500 per hectare.

A comparison between the productivity method and replacement costs method has been done by Gunatilake and Vieth (2000). Both methods provide the same decision guidelines for whether to take conservation techniques, even though replacement cost method provides about 29% higher estimates for on-site costs on the average. In addition, in selecting the best conservation method, the two cost estimates gave different results.

1.3.2 A Threat to Food Security

Soil degradation has been criticized as a threat to food security, especially for developing countries (Brown, 1981; Oldeman, 1999; Scherr, 1999; Pimentel, 2006). Wiebe (2003) projected the production and food security in 2010 for selected developing regions by two partial equilibrium simulation models (i.e. IFPRI's IMPACT model and ERS food security assessment model) with new land degradation data, accounting for reduced area losses and yield losses due to land degradation. Ye and Ranst (2009) constructed a food security index $\mathrm{FSI} = [(\mathrm{s}/\mathrm{g}) - \mathrm{d}]/\mathrm{d}$ to predict the general status of food security for China, where s and d are per capita demand, and g is the expected self-sufficiency level. They considered different scenarios including population growth, urbanization, cropland changes, cropping intensity and soil degradation. Food deficits were predicted to be 3–5%, 14–18% and 22–32% of by 2030–2050 under the zero-degradation, the current degradation rate and double-degradation rate scenarios, respectively.

1.3.3 Off-site Economic Costs

Cost-benefit analysis (CBA) is widely applied in assessing the efficiency impacts of proposed policies (Boardman *et al.*, 2006), including the conservation programs to control soil degradation such as the China's Natural Forest Protection Program and Grain for Green program (GGP). However, to the author's knowledge, there is almost no CBA on China's conservation programs. Peng et al. (2007) estimated the feasibility of GGP in Zhangye area by CBA, but they only include the benefits and costs to farmers based on survey data. Their research must underestimate the benefits from GGP since off-site benefits are omitted. One reason for this might be that the benefits from these programs are hard to estimate due to lack of data, even though some economic methods have been widely developed. This section will review some commonly used methods to evaluate the monetary value of the environmental quality, and some empirical results.

The travel cost method, the damage function method, the replacement cost method and the averting expenditure methods are commonly used to evaluate the costs due to soil degradation[8]. Holmes (1988) employed a sediment damage function and a hedonic cost function to estimate the offsite impact of soil erosion on the water treatment industry, while Hansen et al. (2002) used the averting expenditure method to assess the cost of soil erosion to downstream navigation. Hansen and Ribaudo (2008) divided the off-site benefits from conservation programs into 13

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[8] For more methods, see Lew, D.K., Larson, D.M., Svenaga, H., De Sousa, R., 2001. The beneficial use values database. Department of Agricultural and Resource Economics.

categories, and estimated the per-ton value based on the existing data from literature, as is shown in Table1.3.

Table 1.3. The Soil Conservation Benefit Categories in the US

Categories	Consumer/producer Surplus grain due to	Level	Range of values ($/ton)	Year estimated	Method
Reservoir services	Less sediment in reservoirs	HUC	0-1.38	2007	Replacement costs
Navigation	Shipping industry avoidance of damages from groundings	HUC	0-5.00	2002	Averting expenditures
Water-based recreation	Cleaner fresh water for recreation	HUC	0-8.81	1997	Travel costs
Irrigation ditches and channels	Reduced cost of removing sediment and aquatic plants from irrigation channels	FPR	0.01-1.02	2007	Replacement costs
Road drainage	Less damage to and flooding of roads	FPR	0.20	1986	Averting expenditures
Municipal water treatment	Lower sediment removal costs for water-treatment plants	FPR	0.04-1.45	1989	Damage function
Flood damages	Reduced flooding and damage from flooding	FPR	0.10-0.77	1986	Damage function
Marine fisheries	Improved catch rates for marine commercial fisheries	FPR	0-0.93	1986	Damage function
Freshwater fisheries	Improved catch rates for marine recreational fisheries	FPR	0-0.12	1986	Damage function
Marine recreational fishing	Increased catch rates for marine recreational fishing	FPR	0 to $1.57	1986	Marine recreational fishing model
Municipal & industrial water	Reduced damages from salts and minerals dissolved from sediment	FPR	$0.07 to $1.47	1986	Damage function
Stream protection	Reduced plant growth on heat exchangers	FPR	$0.04 to $1.05	1986	Replacement costs
Dust cleaning	Decrease in cleaning due to reduced wind-borne particulates	FPR	0 to $1.14	1990	Replacement costs

Source: Hansen and Ribaudo (2008)

Note: HUC means Hydrologic Unit Code (HUC) watersheds (2111 HUCs for the continuous States); FPR means Farm Production Regions (10 FPRs for the continuous States)

1.3.4 Incentives to Control

Both theoretical and empirical models are used to analyze the incentives for farmers to adopt control techniques. Studying the theoretical models to describe farmers' decision process on adopting soil conservation techniques is necessary. As Seitz and Swanson (1980) said, if we can model the farmer's soil conservation decision process more completely, we can better understand the process and communicate more effectively with decision makers. Saliba (1985) also wrote "…individual farmers remain the central decision makers with respect to erosion control, a better understanding of these relationships is essential to soil conservation planners and policy makers". A dynamic economic model of maximizing farmers' net present value (NPV) subject to a bunch of constraints is very common in the previous literature. Burt (1981), Clark and Furtan (1983), Collins and Headley (1983) and McConnell (1983) are among the earliest research in this topic. Saliba (1985) reviews these four papers and provides a more complete theoretical model to guide empirical research on the economics of erosion control. This paper also points out "a comprehensive farm-level soil conservation model should include the following variables and functions: functional relationships which capture the impact of farm management choices (the control variables) on soil attributes (the state variables). These are the state equations in an optimal control framework; state variables which reflect changes in soil depth and other productivity related soil characteristics; erosion-productivity linkages which relate changes in soil characteristics to crop yields; crop yield functions which incorporate both soil productivity and management variables so that substitution possibilities between soil and other inputs are explicitly included in the model."

By following the McConnell (1983) model, Barrett (1991) showed that pricing reforms in developing economies will not affect soil conservation dramatically, even though some economists have argued that pricing reforms encourage soil depletion. Milham (1994) developed a comprehensive farm level model for optimum private and social utilization of soil over time, where complexities in the decision process due to environmental conditions and other uncertainties are considered. He concluded that if farmers are well informed, they will tolerate soil degradation only to the point where the marginal net returns from depleting soil depth, fertility or structure equal to the marginal profits foregone from conserving these productive aspects of the soil.

Pagiola (1999) uses a simple graphical model to examine the factors that drive farmers to adopt one land use practice rather than another and the role that government policies might play in encouraging farmers to adopt more conserving practices, and illustrates the results with data from semi-arid Kenya. Hopkins (2001) provides a partial explanation for why farmers may adopt differing conservation strategies, even though they share similar preferences. A model is constructed that divides soil degradation into reversible and irreversible components. Predictions of optimal management response to soil degradation are accomplished using a closed-loop model of fertilizer applications and residue management to control future stocks of soil nutrients and soil profile depth. Antle and Diagana (2003) use the dynamic model to assess the role that soil carbon sequestration could play in helping developing countries deal with soil degradation problems when governments or non-governmental entities take actions to reduce greenhouse gas. A more recent paper by Bond and Farzin (2008) considered both private and social problems by adapting a biogeochemical model of an agroecosystem into an optimal control theory. It contributes to the previous literature in the way that the interrelationship between the human and physical components of the agroecosystem can be modeled in a more realistic context.

In addition to the theoretical models above, some empirical studies examine the factors affect farmers' adoption behaviors. Gould et al. (1989) examined the effect of various factors on the recognition of a soil erosion problem and adoption of soil conservation practices by using a Tobit model. Results showed that farm size, land characteristics, and some socio-economic factors like age and education will affect farmers' recognition of the degradation issues and decisions to control them.

Napier (1991) applies a diffusion model to examine social, economic and institutional factors which affect the adoption of soil conservation practices in developing societies. Factors discussed include awareness of soil conservation practices; potential impacts of adoption; attributes of the innovation; relevance of soil conservation practices; and institutional barriers to adoption. Results indicate that some modest erosion reductions can be achieved at little cost to the farmer by reorganizing production, switching rotations, and using contour plowing. Sharper reductions may be achieved at progressively higher costs as erosion control structures are constructed and acreage is left fallow. Factors such as market imperfections, poverty, high rates of time preference, lack of technologies and land tenure insecurity are found out to undermine Ethiopia's erosion-control investments.

1.3.5 A Threat to Agricultural Sustainability

Agricultural sustainability is a useful concept to motivating agricultural policy changes. Several papers discussed the concepts, definitions, principles and evidence in agricultural sustainability (Carter, 1989; Keeney, 1990; Farshad and Zinck, 1993; Schaller, 1993; Yunlong and Smit, 1994; Hansen, 1996; Raman, 2006; Thompson, 2007; Pretty, 2008). Indicators[9] are commonly used to indicate agricultural sustainability from different dimensions and different spatial scales.

Soil, as one of the most important forms of natural capital, and the associated tillage techniques have also been studied widely under the concept of "agricultural sustainability" (Lal, 1991b, a; Papendick and Parr, 1992; Lal, 1998b; Doran, 2002; Tilman *et al.*, 2002; Brussaard *et al.*, 2007; Montgomery, 2007). As Doran (2002) pointed out, the assessment of soil quality is needed to monitor changes in sustainability and environmental quality as related to agriculture management and to assist governmental agencies in formulating realistic agricultural and land-use policies. Soil quality indicators corresponding to different sustainability strategies have also been developed by Doran (2002). For example, surface soil properties can be used as indicators when soil erosion is minimized by conservation tillage and increased protective cover.

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[9] Sustainability indicators in the literature have been reviewed by Bond, C.A., 2006. Time and tradeoffs in agroecosystem environments: essays on natural resource use and sustainability. UNIVERSITY OF CALIFORNIA, DAVIS.

1.4 Dissertation Organization

In Chapter 2, I develop a dynamic optimization model for soil management and discuss implications for the influence of externalities on intertemporal management of soil capital. This chapter can contribute to the literature by providing a more comprehensive dynamic optimization model for social planners, who are concerned with agricultural sustainability, environmental quality and food security. Tradeoffs between these three objectives are also provided.

In Chapter 3, I employ a multi-output directional distance function approach to estimate the shadow prices of the agricultural pollutants, and further define environment-adjusted profit as a more appropriate term to measure costs from environmental regulations. Specifically, I focus on two pollutants associated with agricultural production activities: soil erosion and nitrogen loss. Further, the most profitable cropping systems are identified if environmental regulations were imposed.

In Chapter 4, I evaluate sustainability for different cropping systems in the Loess Plateau of China using the sustainable value approach, and identify sustainable cropping systems that contribute the most to sustainability.

CHAPTER 2

THE INFLUENCE OF EXTERNALITIES ON INTERTEMPORAL MANAGEMENT OF SOIL CAPITAL: A DYNAMIC PROGRAMMING APPROACH

2.1 Introduction

Natural resources are an important type of capital that have been taken into account by modern growth theorists since Meadows *et al*. (1972) proposed the existence of biophysical "limits to growth". For example, Stiglitz (1974) examined the optimal growth rate for an economy by incorporating natural resources as a substitute for labor and capital into a production function. His model implied that a high rate of technical progress is required to sustain a constant consumption level per capita by offsetting the increasing scarcity of natural resources. Consequently, many have studied the optimal management of natural resources, including groundwater (Culver and Shoemaker, 1992), fossil fuels (Tahvonen, 1997) and fisheries (Bjørndal, 1987), to name just a few.

Soil is an essential form of natural capital for agricultural production. Soil erosion is the natural process of soil depletion that removes topsoil and depreciates soil productivity. About 80% of the world's agricultural land suffers moderate to severe erosion, and during the last 40 years about 30% of the world's arable land has been abandoned from agricultural uses (Pimentel, 2006). Soil erosion adversely affects the productivity of cropland, pasture and rangeland by reducing infiltration rates, water-holding capacity, nutrients, organic matter, soil biota and soil depth (Pimentel *et al.*, 1995), all of which amount to depreciation of this natural capital.

Soil erosion has also been recognized as a major threat to global food security as population expands and scarcity of natural resources increase (Brown, 1981; Wiebe, 2003; Pimentel, 2006; Ye and Ranst, 2009), especially for some food insecure countries (Lal, 2007). For example, Ye and Ranst (2009) predicted that China's food deficits will be 3–5%, 14–18% and 22–32% by 2030–2050 under zero-erosion, current erosion and double-erosion rate scenarios, respectively.

Beyond damages to ecosystem productivity and food security, soil erosion generates a threat to the environment, as large amounts of eroded soil are deposited in water bodies and other ecosystems (Clark *et al.*, 1985; Pimentel *et al.*, 1995; Lal, 1998a; Pimentel, 2006). Hansen and Ribaudo (2008) categorized the off-site impacts of soil erosion in the United States into 13 groups by updating Clark *et al*. (1985), including reservoir services, navigation, water-based recreation, irrigation ditches and channels, road drainage, municipal water treatment, flood damages, marine and freshwater fisheries, marine recreational fishing, municipal and industrial water use, stream protection and dust cleaning. They estimated the monetary value of soil conservation benefits to range from $1to $18 per ton.

Like any other type of capital, depreciation is a function of how it is used to produce goods and services. Soil conservation techniques are proven to reduce the soil depreciation rate significantly (Pimentel *et al.*, 1995). Conservation techniques not only preserve valuable soil capital and maintain crop yield, but also sustain food security and reduce adverse environmental impacts. Off-farm impacts, such as food security and environmental impacts, aren't often internalized in farm profits, and therefore farmers lack incentives to control erosion beyond their own needs without government policy intervention (Hoag *et al.*, 2012).

In soil management, two types of market failures create a difference between conservationists' and farmers' goals toward conservation (McConnell, 1983). One is negative externalities, such as water pollution caused by erosion; the other is that farmers may undervalue productivity losses from intertemporal soil use. The goal of this study is to show that, from a social planner's perspective, it is important to take positive and negative externalities into account when managing natural capital. The management decisions will be misleading if any positive or negative externalities were omitted, and therefore social welfare would not be maximized.

Since natural capital is managed over the long run, a dynamic optimization model is preferable since it can capture the intertemporal tradeoffs related to soil use. Basic dynamic optimization models of soil management can be traced back to Burt (1981), McConnell (1983), and Clark and Furtan (1983). Saliba (1985) pointed out that none of the above models directly incorporated soil productivity and conservation efforts explicitly, and provided a more complete theoretical model, in which farmers maximize the present value of net returns over their planning horizon and land value at the end of their planning horizon by choosing management intensity, crop rotation and soil conservation efforts.

Extensions of the basic models in the literature include Ardila and Innes (1993) , Innes and Ardila (1994) ,Goetz (1997), Hoag (1998), Hopkins et al (2001), and Bond and Farzin (2008). For example, by employing a two-date model and a three-date model to frame soil conservation under uncertainty in both production and end-of-period land price, Ardila and Innes (1993) found that reduced production risk and land price risk will decrease soil depletion in the short run, but long-run effects can't be determined in their models. Hoag (1998) disentangled the impacts of soil erosion into substitution, mixing and depth effects by incorporating a single soil productivity index into the optimization model, and suggested that non-uniform soil profiles should be managed in different ways.

As economists know more about the erosion process and agroecosystem modeling, optimal control decisions are studied in a more complex and realistic context. For example, Hopkins et al (2001) constructed a model that divides soil degradation into reversible nutrient depletion and irreversible soil depth loss, in which fertilizer application and residue management are chosen by farmers. A biogeochemical model of nutrient cycling and storage was built into an optimal control theory framework by Bond and Farzin (2008), which allows analyzing the long-term impacts of tillage and residue management on nutrient pools and farmers' fertilization decisions under the concept of agricultural sustainability. However, negative externalities from erosion have only been considered in a few studies (McConnell, 1983; Bond and Farzin, 2008), even though off-site impacts from water erosion are estimated to be 3-14.5 times as much as soil productivity impacts (Hansen and Ribaudo, 2008).

This chapter will develop a more comprehensive dynamic optimization model of soil management, by incorporating positive externalities, such as food security from soil capital, and negative externalities, such as environmental pollution from soil erosion, explicitly into a social welfare function for a public model. A private model is developed as a comparison, in which farmers maximize the present value of net returns across a time horizon without accounting for externalities. The comparison between the public and private models will provide some implications for the tradeoff between the welfare in current period and in the future. This chapter is organized as follows. Section 2.2 discusses the two externalities incorporated in the public model, i.e. food security and environmental pollution. The private and public dynamic optimization models are described in Section 2.3. An example is given in Section 2.4 to verify the theoretical models. Section 2.5 discusses and concludes this study.

2.2 Externalities and Soil Management

2.2.1 Food Security and Sustainable Soil Management

As agreed upon at the World Food Summit (1996), food security is defined as "all people, at all times, have physical and economic access to sufficient safe and nutritious food to meet their dietary needs and food preferences for a healthy and active life" (Pinstrup-Andersen, 2009, pp.5). A complete concept of food security includes four components, i.e. availability, stability, access and utilization (Schmidhuber and Tubiello, 2007). *Availability* implies that agricultural systems are capable of producing and distributing food to meet people's demand. *Stability* exists when there is no possibility for agricultural systems to suffer temporal or permanent risk of losing their capacity to provide adequate food. *Access* ensures that people have enough monetary resources and traditional rights to acquire appropriate food. *Utilization* encompasses all food safety and quality aspects of nutrition.

Several studies provide the evidence that soil erosion threatens food security at the household, national and global levels (Brown, 1981; Oldeman, 1999; Scherr, 1999; Pimentel, 2000; Stocking, 2003; Wiebe, 2003; Lal, 2009). Soil erosion adversely affects food security in several ways (Figure 2.1). First, erosion-induced loss in soil productivity reduces crop yield, and therefore limits food availability to farmers as well as the nation. Second, limited farm incomes caused by crop yield loss prevent farmers from protein uptake and dietary diversity. Lack of protein in farmers' diet reduces their nutrition level. Third, erosion induced environmental pollution undermines national food and water safety. Toxic chemicals associated with erosion, such as heavy metals and pesticides, lead to contaminated food and water resources (Pimentel *et al.*, 2007). Fourth, erosion generates sedimentation and pesticide into river, lake and ocean, which causes water pollution and reduces fishery supply. This will restrict people's access to fish as one of protein source, and therefore affect their nutrition level. Some factors can exacerbate or offset the adverse effects of soil erosion on food security, such as population growth, climate change, technological progress and trade policies.

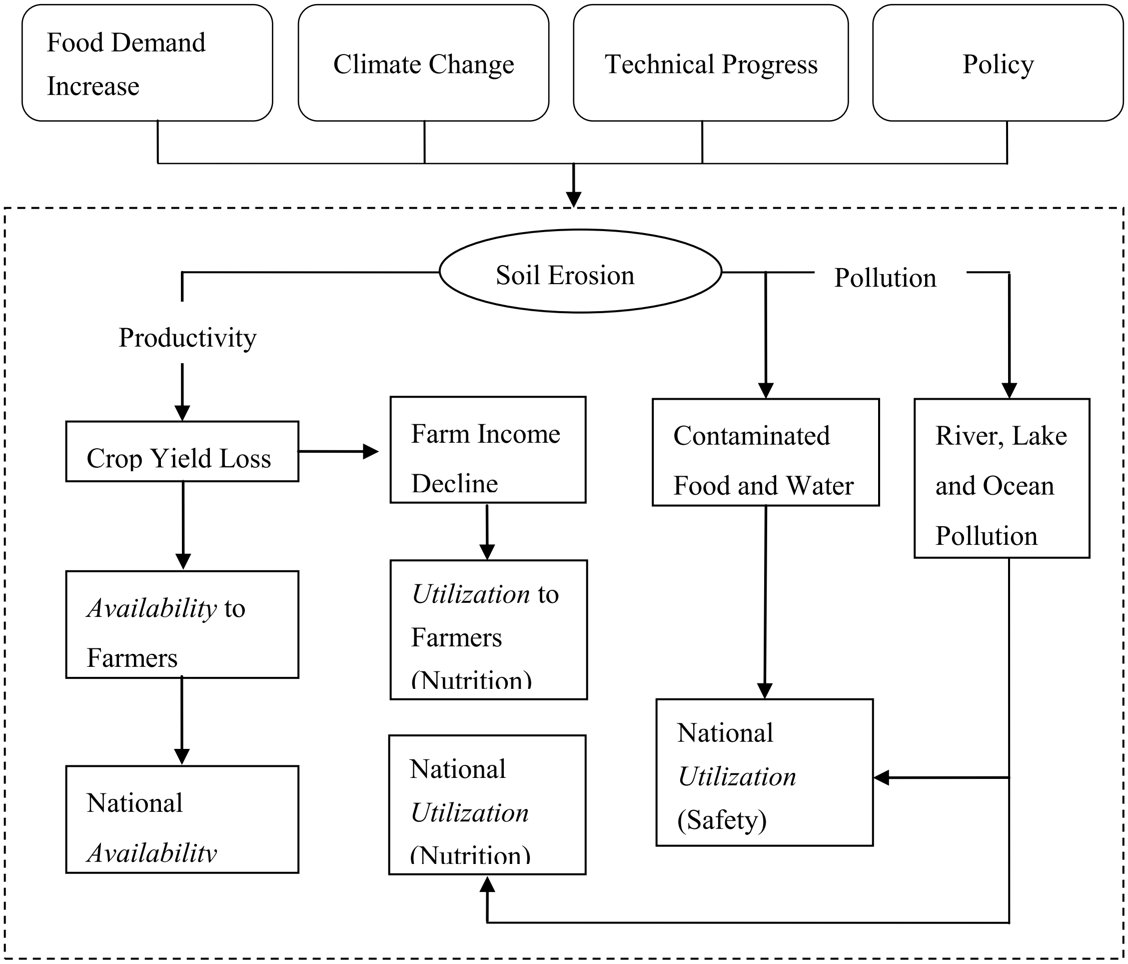

Figure 2.1. Effects of Soil Erosion on Food security

Food security is a positive externality, further a *public good*, because it is virtuously non-rivalrous and non-exclusive (Rocha, 2007). Each individual benefiting from living in a food secure society will not reduce other people's benefits (Non-rivalrous). And it would be pointless to accomplish food security and prevent some individuals from enjoying the benefits of living in that food secure society (Non-exclusive). Soil management, however, is a *private behavior*. The adverse effects of soil erosion on food security in the future will not be taken into account by rational farmers without any government intervention. Thus, a difference in optimal soil management exists between the private and public problems. Policy makers and governors, who view food security as a national strategic goal, will be interested in the optimal path of soil management when food security is considered.

2.2.2 Environmental Pollution and Sustainable Soil Management

The erosion and runoff processes creates a set of potential pollutants including the resulting sediments and associated contaminants (Clark *et al.*, 1985). These pollutants are transported into and through waterways, where they can directly or indirectly cause various costs to those who consume the environmental services. A summary of types of environmental impacts and their processes is provided in Table 2.1. These impacts are divided into in-stream effects and off-stream effects. For example, the sedimentation occurring in harbors, bays, and navigation channels reduces the capacity of these facilities to handle commercial and recreational craft, increases the likelihood of shipping accidents, and requires expensive dredging to keep the facilities usable.

Table 2.1. Summary of Environmental Impacts from Soil Erosion and Their Process

Type of Impacts	Impact process
In-stream effects	
Biological	Turbidity and sedimentation cause damage either directly, through physically or biologically affecting aquatic organism itself, or indirectly, through destroying the organism's required habitat.
Recreational	High turbidity probably reduces the pleasure of swimming and boating; Turbidity and sedimentation can significantly decrease the quality of sports fishing; can diminish the quality of the recreational experience.
Water-storage facilities	Reduce lakes and reservoirs' water-storage capacity, changing the temperature of the water, and providing increased opportunities for the growth of water-consuming plants.
Navigation	The sedimentation occurring in harbors, bays, and navigation channels reduces the capacity of these facilities to handle commercial and recreational craft, increases the likelihood of shipping accidents, and

	requires expensive dredging to keep the facilities usable.
Other in-stream uses	Hydroelectric and other machinery that operates in water
Off-stream effects	
Flood damages	In any stretch where a streambed has aggraded, the elevation of the water surface associated with any volume of flow will be higher and may flood adjacent land in the absence of what would otherwise be a flood flow.
Water-conveyance facilities	Sedimentation will require increased maintenance efforts to remove sedimentation; high turbidity can increase the cost of pumping water from its source.
Water-treatment facilities	Both the investment and the operation and maintenance costs of the water-treatment facility will increase as the turbidity of a water supply increases.
Other off-steam uses	Suspended sediment in irrigation water can form a crust on a field, reducing the amount of water that seeps into the soil, inhibiting the emergence of plants, and preventing adequate soil aeration. Sediment may also coat the leaves of young plants.

Source: adapted from Clark et al. (1985)

Environmental pollution from soil erosion is a negative externality to farmers who manage their soil, which will not be internalized by their private decision. Again government interventions, such as conservation programs, are needed to correct this market failure. Policy makers will be concerned with the optimal soil management accounting for environmental pollution as a negative externality, if they aim to build an environment-friendly society.

2.3 Model Description and Optimization Technique

I build two dynamic optimization models in this section, i.e. a private model and a public model, to compare the soil management strategies and to balance welfare in current period and in the future. By continuing previous literature, I assume in the private problem, a typical producer maximizes the present value of net returns over an infinite time horizon, by choosing soil management techniques, subject to the dynamic changes of soil properties. In the public model, a social planner maximizes total welfare by incorporating food security as a positive externality from soil capital and environmental pollution as a negative externality from soil erosion into a social welfare function over an infinite time horizon.

2.3.1 Soil Properties and Soil Erosion

Soil has multiple properties, including total soil nitrogen, water-holding capacity, soil depth, pH and so on. Soil erosion is a complex process involving a detachment of individual soil particles from the soil mass, their transportation by water and wind, and deposition (Morgan, 2005). Soil is divided into reversible and irreversible components as suggested by Hopkins et al. (2001) to make my economic model succinct but without losing generality of representing the multidimensionality of soil properties and erosion. *Nutrient depletion* is portrayed as a reversible facet of soil erosion, since appropriate fertilization can compensate for nutrient loss. *Soil depth depletion* is viewed as irreversible since natural soil formation rate is very slow and it is not economically feasible to enhance soil depth. Nutrient depletion adversely affects environmental quality by transporting soil nutrients and toxic chemicals into water and air; soil depth depletion generates sedimentation and reduces the water holding capacity of waterways.

The soil nutrient cycling process, including nutrient depletion, has been studied by soil scientists in detail and built into complex agroecosystem simulation models such as CENTURY developed by Parton et al. (1987) and EPIC by Williams et al. (1983). But these models are too complex for economists to incorporate them into a dynamic optimization model, and will dilute the major economic issues. A simplified nutrient cycling process is chosen and illustrated in

Figure 2.2. The nutrient available for crop growth is a state variable in the dynamic model, represented by the box in the middle. Two main gains are from the atmosphere and fertilization. Two major losses are from leaching/runoff and harvest. The soil nutrient in time $\mathbf{t+1}$ is equal to the soil nutrient in time $\mathbf{t}$ plus soil nutrient gains from atmosphere and fertilization, minus the nutrient loss from leaching and harvest. Thus, mathematically, the nutrient cycling process can be specified as:

$$\mathbf{N_{t+1} = N_t + n(F_t) - m(SC_t, F_t) + \overline{NB}_t}, \qquad \text{Equation 2.1}$$

where $\mathbf{N_{t+1}}$ and $\mathbf{N_t}$ are the soil nutrient levels in time $\mathbf{t+1}$ and $\mathbf{t}$, $\mathbf{n(F_t)}$ is nutrient gain from fertilization and $\mathbf{F_t}$ is applied fertilizer, $\mathbf{m(SC_t, F_t)}$ is soil nutrient loss from leaching and harvest, affected by soil conservation efforts $\mathbf{SC_t}$ and applied fertilizer $\mathbf{F_t}$, and $\mathbf{\overline{NB}_t}$ captures others factors such atmosphere and nutrient pool exchange to balance this process.

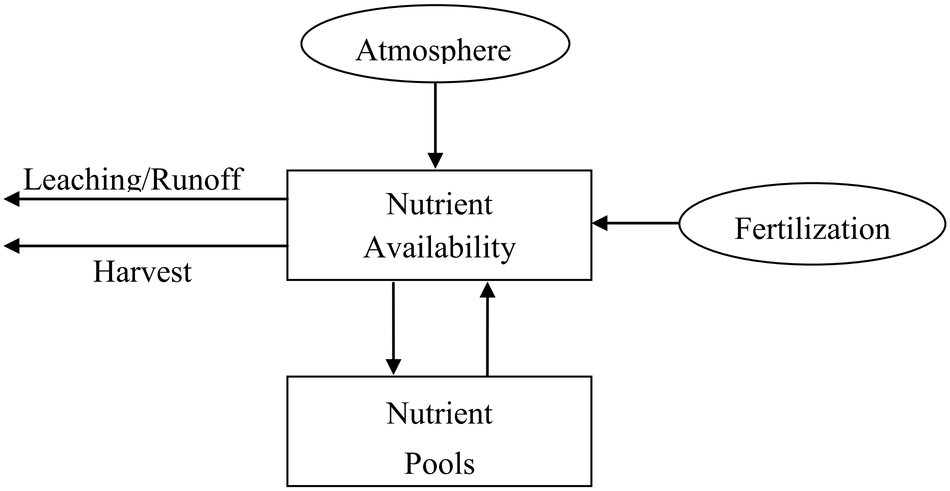

Figure 2.2. Conceptual Diagram for Nutrient Cycling

Source: Adapted from Bond and Farzin (2008)

Soil depth is another state variable in my dynamic model. Soil depth depletion depends on several factors such as land slope, vegetation, rainfall amount and intensity, and conservation techniques (Montgomery, 2007). However, the only direct conservation management factor is conservation effort. Thus, the dynamic process of soil depth depletion can be specified as:

$$\mathbf{SD_{t+1} = SD_t - s(SC_t) + \overline{SB}_t,} \qquad \text{Equation 2.2}$$

where $\mathbf{SD_{t+1}}$ and $\mathbf{SD_t}$ are soil depth in time $\mathbf{t + 1}$ and $\mathbf{t}$, $\mathbf{s(SC_t)}$ is soil depth depletion in time $\mathbf{t}$ depending on the conservation efforts in time $\mathbf{t}$ $(\mathbf{i.e. SC_t})$, and $\mathbf{\overline{SB}_t}$ is soil building rate during time t.

2.3.2 Crop Production and Profit

Labor, capital and land are the three conventional inputs involved in a production function for crop yield. To capture the effects of soil erosion on crop yield, the soil nutrient level, as the reversible component, and the soil depth level, as the irreversible component, are incorporated into a production function as follows:

$$\mathbf{Y_t = e^{\rho t} y(SD_t, N_t, SC_t),} \qquad \text{Equation 2.3}$$

where $\mathbf{e^{\rho t}}$ represents technological progress, where $\boldsymbol{\rho}$ is the rate of technological progress; crop yield in time $\mathbf{t}$, $\mathbf{Y_t}$, is a function of soil depth $\mathbf{SD_t}$, soil nutrient level $\mathbf{N_t}$ and soil conservation efforts $\mathbf{SC_t}$.

The profit function from growing a crop in time $\mathbf{t}$ is:

$$\boldsymbol{\pi_t} \mathbf{= p_y Y_t - c_{SC} SC_t - c_F F_t - \bar{C},} \qquad \text{Equation 2.4}$$

where $\boldsymbol{\pi}_\mathbf{t}$ is profit in time $\mathbf{t}$, $\mathbf{p_y}$ is crop price, $\mathbf{c_{SC}}$ is the per unit cost of conservation, $\mathbf{c_F}$ is the per unit cost of fertilizer, $\mathbf{Y_t}$ is crop production, $\mathbf{SC_t}$ and $\mathbf{F_t}$ are conservation efforts and applied fertilizer, $\bar{\mathbf{C}}$ is the corresponding fixed cost.

2.3.3 Environmental Pollution

Environmental pollution, as shown in Table 2.1, can be categorized into nutrient-related and sedimentation-related damages. From Equation 1.1 and 1.2, soil nutrient depletion is affected by soil conservation efforts and applied fertilizer, while soil depth depletion is a function of only conservation efforts. Thus, the change in environmental pollution from time t+1 to t is a function of soil conservation and applied fertilizer. In mathematical form, it is expressed as:

$$\mathbf{X_{t+1} = X_t + x(SC_t, F_t) - \overline{XB}_t,} \qquad \text{Equation 2.5}$$

where $\mathbf{X_{t+1}}$ and $\mathbf{X_t}$ are environmental pollution level in time t+1 and t, $\mathbf{x(SC_t, F_t)}$ is the environmental pollution worsened by less conservation efforts and overuse of fertilizer, $\mathbf{\overline{XB}_t}$ represents the self-maintenance of ecosystem in reducing pollution.

2.3.4 Food Security

As discussed in Section 2.2.1, food security is a multidimensional concept including availability, stability, access and utilization at household, regional, national and global levels. On a macro level, food security can be indicated by the number of malnourished children, as in IFPRI's IMPACT model, or assessed by measuring the size of and trends in several alternative food gaps, as in the ERS model (Wiebe, 2003). On a micro level, household surveys are used as a tool to measure household food security by USDA (Bickel *et al.*, 2000). However, the Chinese government almost exclusively views food security as food self-sufficiency or even grain-self sufficiency (Ye and Ranst, 2009). Self-sufficiency is measured by the percentage of domestic food production over total consumption. A grain self-sufficiency level of 95% has been adopted as a strategic goal for maintaining food security in China from 2008 to 2020 (NDRC, 2008).

To account for the self-sufficiency goal and other dimensions of food security, a food security index is defined here as the ratio of food supply over food demands while considering trade uncertainties, population growth and dietary change. The food security index (FSI) in its mathematical form is:

$$\mathbf{FSI_t = \frac{S_t}{D_t} = \frac{A_t\left(Z_{a,t}\right)Y_t(SD_t, N_t, SC_t, \rho) + IM_t\left(Z_{im,t}\right)}{D_{t-1}(1+g_t)(1+d_t)}}$$

Equation 2.6

where $\mathbf{FSI_t}$ is the food security index in time $\mathbf{t}$; $\mathbf{S_t}$ and $\mathbf{D_t}$ are the overall supply and demand in time $\mathbf{t}$; $\mathbf{A_t\left(Z_{a,t}\right)}$ is the crop acreage in time $\mathbf{t}$ and affected by factors $\mathbf{Z_{a,t}}$, such as urbanization; $\mathbf{Y_t(SD_t, N_t, SC_t)}$ is the crop production function accounting for technological progress, described in Equation 3; $\mathbf{IM_t\left(Z_{im,t}\right)}$ is grain imports in time t and affected by factors $\mathbf{Z_{im,t}}$, such as trade barrier; $\mathbf{D_{t-1}}$is the demand in time $\mathbf{t-1}$; $\mathbf{g_t}$ is the population growth rate in time $\mathbf{t}$; $\mathbf{d_t}$ is the dietary change rate in time $\mathbf{t}$. The reduced form of FSI can be written as:

$$\mathbf{FSI_t = f(Z_{a,t}, SD_t, N_t, SC_t, Z_{im,t}, g_t, d_t)}$$

Equation 2.7

2.3.5 Private Model

In the private model, a rational farmer representative is assumed to maximize the present value of net return from cropping over an infinite time horizon by choosing applied fertilizer and conservation efforts.

Formally, the private model can be defined as:

$$\max_{\mathbf{SC_t, F_t}} \sum_{\mathbf{t=0}}^{\infty} \boldsymbol{\delta}^{\mathbf{t}} \boldsymbol{\pi}_{\mathbf{t}}\left(\mathbf{SD_t, N_t, SC_t, F_t; p_y, c_{SC}, c_F, \bar{C}}\right)$$

$$\text{subject to} \quad \mathbf{N_{t+1} = N_t + n(F_t) - m(SC_t, F_t) + \overline{NB}_t}$$

$$\mathbf{SD_{t+1} = SD_t - s(SC_t) + \overline{SB}_t}$$

Equation 2.8

where $\boldsymbol{\delta}$ is a discount factor between 0 and 1, and all other variables have been previously defined.

2.3.6 Public Model

In the public model, a social planner is assumed to maximize social welfare across an infinite time horizon under the consideration of positive externalities, e.g. food security, and negative externalities, e.g. environmental pollution. Social welfare is assumed to be a function of producers' profit $\boldsymbol{\pi}_{\mathbf{t}}$, the food security index $\mathbf{FSI_t}$, and environmental pollution $\mathbf{X_t}$. Assuming additive separability among the three components, the social welfare function in its mathematical form can be written as:

$$\boldsymbol{\omega_t = \omega(\pi_t, FSI_t, X_t)}.$$ Equation 2.9

Social welfare is increased with farmers' profit and national food security status, but decreased with environmental pollution, i.e.

$$\frac{\partial \omega_t}{\partial \pi_t} > 0; \frac{\partial \omega_t}{\partial FSI_t} > 0; \frac{\partial \omega_t}{\partial X_t} < 0.$$

Equation 2.10

Formally, the public model is defined as:

$$\max_{SC_t, F_t} \sum_{t=0}^{\infty} \delta^t \omega_t(\pi_t, FSI_t, X_t)$$

subject to $$N_{t+1} = N_t + n(F_t) - m(SC_t, F_t) + \overline{NB}_t$$

$$SD_{t+1} = SD_t - s(SC_t) + \overline{SB}_t$$

$$X_{t+1} = X_t + x(SC_t, F_t) - \overline{XB}_t$$

Equation 2.11

where $\boldsymbol{\delta}$ is a discount factor between 0 and 1, and all other variables have been defined above.

2.3.7 Optimization Technique: The Bellman Equation

The private model and public model described above are two examples of dynamic optimization. Specifically, the private model is a discrete time dynamic model with two continuous state variables (i.e. SD and N) and two continuous action variables (i.e. SC and F), while the public model has three continuous state variables (i.e. SD, N and X) and two continuous action variables (i.e. SC and F). All of the dynamic processes of state variables in these two examples follow a controlled Markov probability law; thus Bellman's Principle of Optimality can be utilized to solve these two models. The Principle can be formally expressed by a value function V_t, which must satisfy Bellman's equation (Miranda and Fackler, 2004).

For the private model, the Bellman's equation is:

$$\mathbf{V_t(SD, N) = \max_{SC,F}\{\pi_t(SD, N; SC, F) + \delta_1 V_{t+1}[\pi(SD, N; SC, F)]\}}$$

Equation 2.12

where V_t is the value function for the farmer representative (i.e. the maximum of current and future returns), δ_1 is the discount rate for the farmer representative. Technology is ignored for the time being.

For the public model, the Bellman's equation is

$$\mathbf{U_t(SD, N) = \max_{SC,F}\{\omega_t(\pi, FSI, X) + \delta_2 U_{t+1}[\omega(\pi, FSI, X)]\}}$$

$$\mathbf{= \max_{SC,F}\{\omega_t(SD, N, X; SC, F) + \delta_2 U_{t+1}[\omega(SD, N, X; SC, F)]\}}$$

Equation 2.13

where U_t is the value function for a social planner (i.e. the maximum of current and future welfare), δ_2 is the discount rate for the social planner.

The value function for the private model is the maximized sum of current returns and all future discounted returns. The tradeoff between current returns and all future returns is explicitly embedded in the Bellman equation for the private model. Similarly, the value function for the public model is the maximized sum of current welfare and all future discounted welfare. The tradeoff between current welfare and all future welfare is explicitly embedded in the Bellman equation for the public model. Since food security and environmental pollution affects social welfare, the optimal policy path will be different between the private and public model. For example, in the private model, optimal conservation efforts should be chosen at the point where the marginal cost of conservation to farmers in the current period is equal to the marginal profit of conservation in all the future periods. In the public model, the optimal conservation should be chosen at the point where the marginal welfare loss from conservation costs in the current period is equal to the marginal welfare gain of conservation in all the future periods.

There are no closed-form solutions to the Bellman equations here, therefore the model can only be solved approximately using computational methods (Miranda and Fackler, 2004). To verify and explore more from the conceptual model, an empirical example is described and solved by the collocation method[10] in the following section.

2.4 An Empirical Example

An empirical example is applied to demonstrate the approach and to better understand the concepts. Data for the empirical example are from previous literature.

2.4.1 Model Parameters

Some estimated functions from previous literature are employed in this section to construct the empirical dynamic models (Table 2.2). I did not parameterize the conceptual models because

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[10] For more information on the collocation method, refer to Chapter 9. Discrete Time Continuous State Dynamic Models: Methods. Miranda, M. J. and P. L. Fackler (2004). Applied computational economics and finance. Cambridge, Massachusetts, The MIT Press.

of the limited data. In these empirical dynamic models, one continuous state variable and one continuous choice variable are considered. The percentage of crop residue left on the ground is the action variable, denoted by R, used to approximate the conservation efforts. Soil depth as the state variable, denoted by SD, is used to approximate the soil properties. Soil erosion depends on the percentage of crop residue left on the ground, and therefore the transition function is:

$$\mathbf{SD_{t+1} = SD_t + g(R).}$$

These simplifications will not affect interpretation of the impacts and tradeoffs when accounting for negative and positive externalities. I adopted a stylized function presented by Reeder (1992) and also used by Hopkins (2001), for the measurement of soil erosion in inches, i.e.$\mathbf{g(R) = -\alpha 0.96 \cdot 10^{-0.013R}}$, where $\boldsymbol{\alpha}$ is the annual erosion rate for bare soil in inches of topsoil depth. I took $\boldsymbol{\alpha}$ equal to 1.5 inches per year.

The crop production in time t depends on soil depth in the same period. Mathematically, the production function is:

$$\mathbf{Y_t = y(SD_t).}$$

The estimated yield function is taken from Walker (1982), i.e.$Y_t = 36.44 + 47.01(1 - e^{-0.09864\,SD_t})$, where $\mathbf{Y_t}$ is wheat yield in bu./acre and SD_t is soil depth in inches.

The reward function in the private model is:

$$\boldsymbol{\pi_t(SD_t, R_t) = p_y y_t(SD_t) - C(R_t) \cdot R_t,}$$

where $\pi_t(SD_t, R_t)$ is the profit function in time t, depending on soil depth, SD_t, and the percentage of crop residue left on the ground, R_t, in the same period. The profit equals the crop revenue minus the costs for conservation efforts. Wheat price is denoted by p_y and equal to \$ 3/bushel in this example. The function $C(R_t)$ gives the marginal costs for any level of residue management, and the function $C(R_t) = 10^{(-1.1372+0.0364 R_t)}$ was estimated by Hopkins (2001).

The private model can be written as:

$$\max_{R_t} \sum_{t=0}^{\infty} \delta^t \left[p_y y_t(SD_t) - C(R_t) \cdot R_t\right]$$

$$\text{subject to:} \quad SD_{t+1} = SD_t + g(R_t)$$

$$0 \leq R_t \leq 100,\ 0 \leq SD_t \leq 40,$$

where δ is the discount factor, and equal to 0.95 in this example; the percentage of crop residue left on the ground is between 0 and 100; the topsoil depth is between 0 and 40 inches.

Food security index developed in Section 2.3.4 is a comprehensive index, but it is difficult to estimate the parameters for this dynamic model. From now on, I assume food security in time t as a function of soil depth in the same period for simplicity, i.e. $FS_t = FS(SD_t)$. To make the welfare generated by farm profit and food security comparable, I adopt a functional form for food security similar to that for farm revenue, i.e. $FS_t = p_{FS} \cdot y(SD_t) = p_{FS}[36.44 + 47.01(1 - e^{-0.09864 SD_t})]$, where p_{FS} is the value on food security in terms of dollars per unit of crop. I choose an arbitrary number \$2/bu., which is about 67% of the crop price.

The environmental pollution is expected to increase with total soil loss. I assume the monetary value of per unit of environmental pollution is \$5/inch. This means an inch soil loss will cause \$5 loss to the recreationists. So it can be specified as a function of total soil loss, i.e. $X_t = x(SD_0 - SD_t) = 5 \cdot (40 - SD_t)$, where SD_0 is soil depth in time t = 0, and is assumed to be 40 inches here.

The public model can be written as:

$$\max_{R_t} \sum_{t=0}^{\infty} \delta^t \{ [p_y y_t(SD_t) - C(R_t) \cdot R_t] + p_{FS} \cdot y(SD_t) - X_t$$

$$\text{subject to:} \quad SD_{t+1} = SD_t + g(R_t)$$

$$0 \le R_t \le 100, 0 \le SD_t \le 40.$$

The difference between the private and public model lies in the reward function. The welfare from food security and environmental pollution is taken into account in the reward function of the public model.

Table 2.2. Key Parameters Used in Dynamic Models

Parameter	Value	Source
$\mathbf{g(R)}$	$-1.5 \cdot 0.96 \cdot 10^{-0.013R}$	Reeder (1992)
$\mathbf{y(SD_t)}$	$36.44 + 47.01(1 - e^{-0.09864 SD_t})$	Walker (1982)
$\mathbf{C(R_t)}$	$10^{(-1.1372 + 0.0364 R_t)}$	Hopkins (2001)
$\mathbf{FS_t}$	$2 \cdot y(SD_t)$	By the author
$\mathbf{X_t}$	$5 \cdot (40 - SD_t)$	By the author

2.4.2 Optimal Solutions

Soil depth time paths and crop residue management time paths are given in Figure 2.3 and Figure 2.4. A solid line is used to denote the time path implied by the private model, a line with filled dots for the public model only considering environmental pollution, a dotted line for the public model only considering food security, and a line with open circles for the public model with both environmental pollution and food security. As expected, the soil depth time path for the private model is the steepest, meaning erosion the highest, among the four models; the soil depth time path for the public model with both environmental pollution and food security is the flattest (Figure 2.3). Correspondingly, the conservation efforts are higher when both externalities are taken into account than that only farm profit is considered (Figure 2.4). This implies that the soil erosion rate is higher and conservation efforts are lower when farmers maximize their present value of net returns than that when both positive and negative externalities are also considered. However, this does not indicate how negative and positive externalities are driving the systems, separately. The dotted line and the line with filled dots in Figure 2.3 and 2.4 imply that environmental pollution caused by erosion and food security generated by soil capital drives soil management to the same direction. Both of them require a less erosive management, i.e. more conservation efforts.

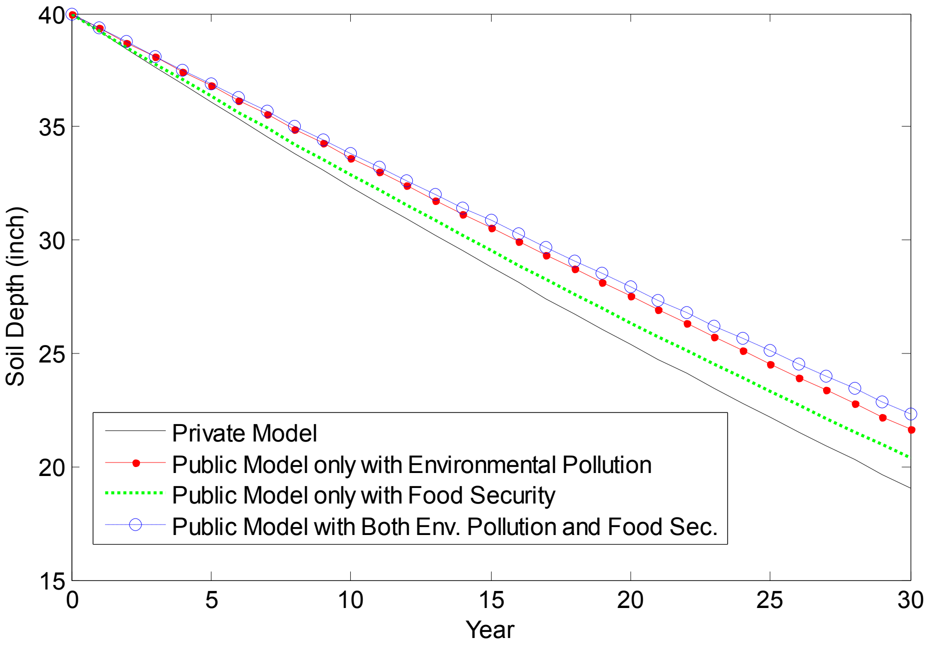

Figure 2.3. Soil Depth Time Path

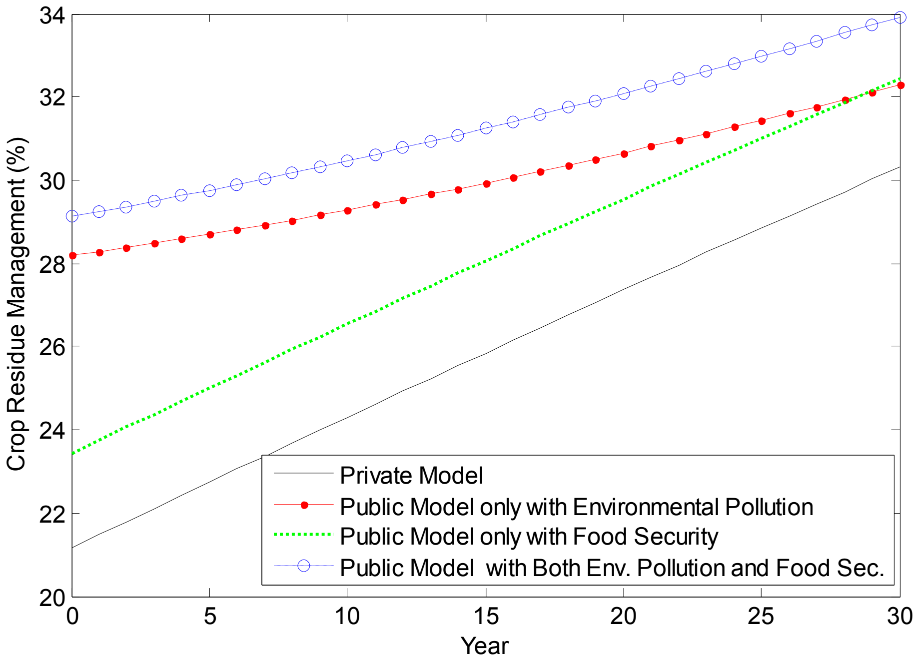

Figure 2.4. Crop Residue Management Time Path

The corresponding paths of farm profit, production and total welfare are given in Figure 2.5-2.7. The farm profit path for the private model lies above those for the public models (Figure 2.5).

This implies that farmers lose profit when environmental pollution and food security are taken into account. One reason is that the costs associated with higher conservation efforts for reducing environmental pollution and enhancing food security are imposed on farmers. The difference in farm profit between the private model and the public model, with both environmental pollution and food security, can be used to approximate the subsidy needed to entice farmers to adopt conservation measures. For example, at the starting year, farm profit in the private model is about \$238 and only \$223 in the public model. Farmers would need to be paid \$15 to adopt more conservation techniques in order to manage consistently with social objective. Again, both environmental pollution and food security drive farm profit to the same direction, i.e. causing profit loss.

The yield paths for the three public models lie above that for the private model (Figure 2.6). This implies that the yield is higher when environmental pollution and/or food security are considered than when only farm profit is considered. Food security is directly related to the crop production. The line with filled dots for the public model that account for environmental pollution lies above the black line for the private model and implies that considering the impacts of environmental pollution will enhance food security, instead of undermining food security.

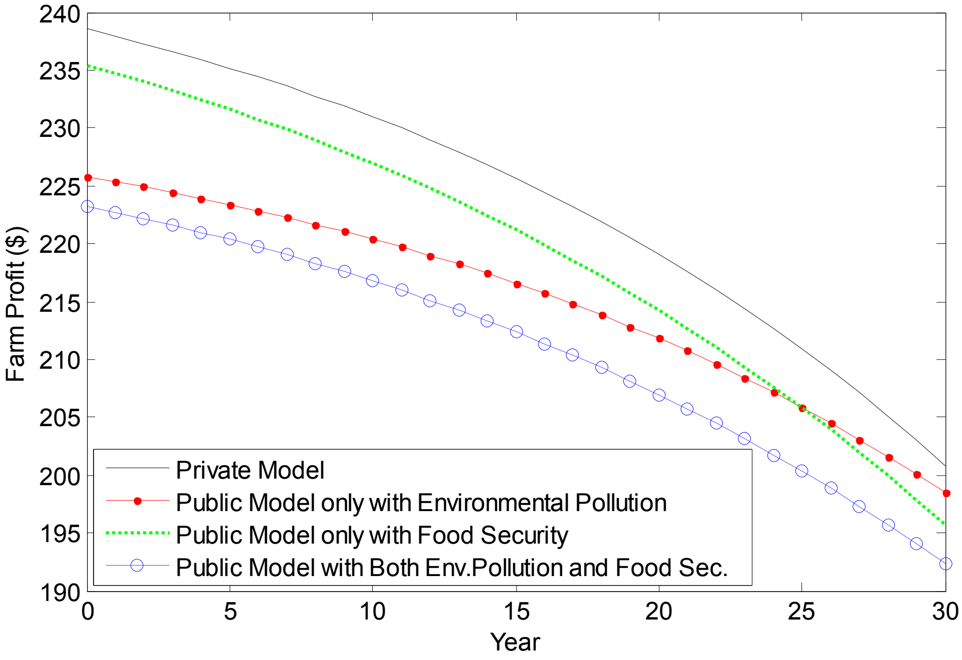

Figure 2.5. Farm Profit Time Path

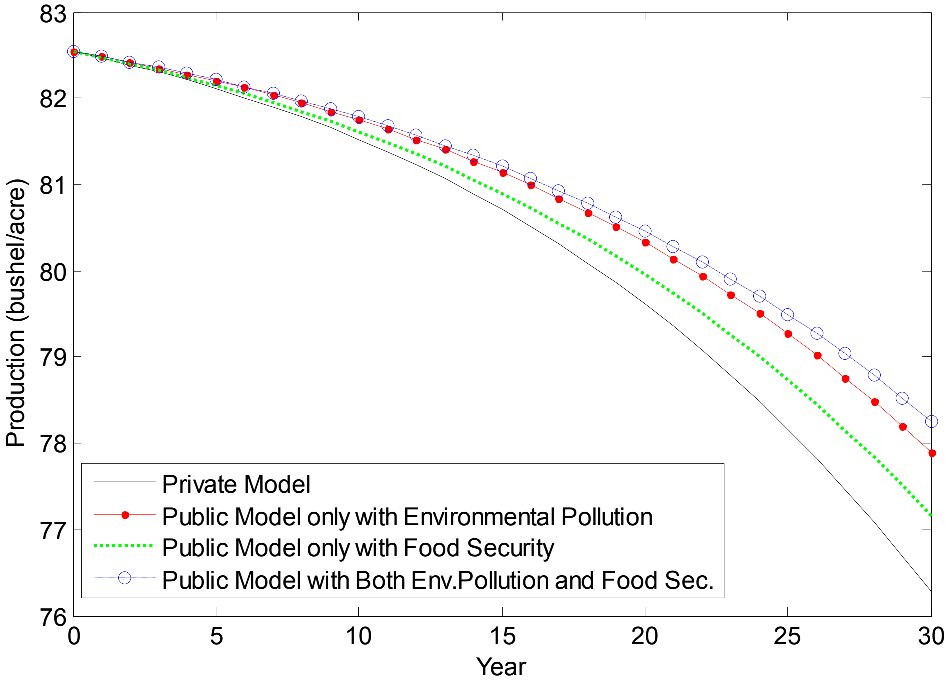

Figure 2.6. Crop Yield Time Path

Finally, welfare for each model is shown in Figure 2.7. The welfare in the private model is higher than that in the public model in the first 15 years, but the opposite afterward. This implies that there exists an intertemporal tradeoff in welfare. To maintain a higher level of welfare in the future, more conservation efforts are needed in the present. The sum of all welfare benefits in the public model is greater than in the private model.

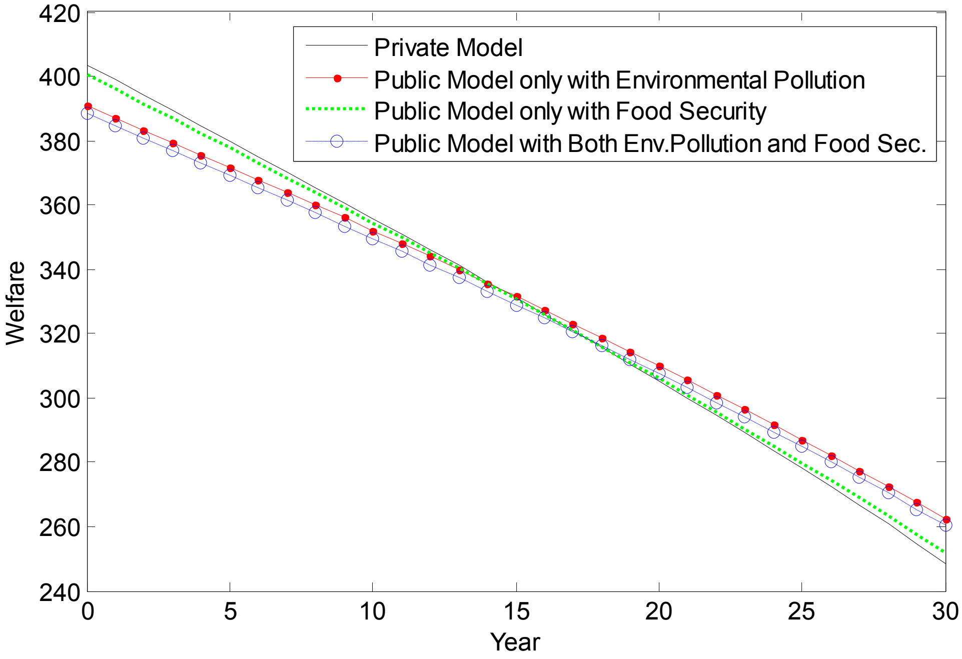

Figure 2.7. Total Welfare Time Path

2.5 Discussion and Conclusions

A dynamic optimization model of soil management has been studied in previous literature. However, it lacks incorporating positive and negative externalities into a social welfare function. The optimal soil management strategies will be misleading if the externalities are ignored in making decisions. A more comprehensive dynamic optimization model was built in this chapter by taking food security as an example of positive externalities and environmental pollution as an example of negative externalities into account. The Bellman equations show the tradeoff between the current return and the future returns. A comparison between the Bellman equations for the private model and the public model theoretically shows which factors affect the externalities and how externalities affect total welfare matters to the optimal path.

An empirical example was computed by the collocation methods to explore more about the dynamic optimization models. Because of the limited data, the empirical results only provide the direction of the effects instead of the exact amount. The results are summarized as follows. First, the private optimal soil management strategy is different from that when externalities are considered. More conservation efforts are needed if externalities are considered. Second, a policy to enhance food security, such as preserving soil capital, is complementary to reducing environmental pollution, and vice versa. Third, farmers will lose some profit if conservation programs were implemented to meet the optimal conservation path implied by the public model including the impacts of food security and environmental pollution. The difference in farm profit between the private and public model offers an estimate of the necessary subsidy to farmers to adopt conservation measures. Fourth, an intertemporal tradeoff exists in welfare. A higher welfare will only be achieved in the first few years if the externalities were ignored, such as in the private model. Although a lower welfare is associated with the optimal policy when the externalities are considered in the first few years; therefore, a higher welfare will be achieved in the long run. In other words, if the externalities were ignored, there would be a welfare gain in the first few years, sacrifices in the future. From a sustainability standpoint, the externalities should be taken into account since the corresponding welfare will last longer.

CHAPTER 3

SHADOW PRICING ABATEMENT COSTS OF AGRICULTURAL POLLUTANTS IN THE LOESS PLATEAU OF CHINA

3.1 Introduction

The Loess Plateau in China is characterized by steeply sloped land as well as poor soil and crop management. It is known for low productivity and serious soil and water losses (Lu *et al.*, 2003). Combined with its large population and pervasive poverty, this fragile environment raises concerns about agricultural sustainability from farmers, agronomists, agricultural economists and ecologists alike (Liu, 1999). Resource degradation from erosion and agricultural pollutants is a major threat to agricultural sustainability. Soil erosion, exacerbated by some intensive agricultural practices, undermines soil productivity and threatens food security; it also degrades ecological functions.

Off-farm environmental degradation generated by agricultural pollutants does not typically have an impact on farm profits, and is therefore overlooked by many farmers. Policy intervention such as regulations or taxes would be required for farmers to account for these impacts in their decisions (Hoag *et al.*, 2012). Such support was provided in the Loess Plateau through the Grain for Green program, which paid farmers to convert steeply sloped cropland to grassland and/or forest.

However, with some land out of agricultural production, more intensive agricultural practices are increasingly employed to feed a burgeoning population (Chen *et al.*, 2007). This will offset some benefits from the Grain for Green program. For some family farms whose land had been mostly planted to trees through the Grain for Green program, young male labors had to migrate to and work in urban areas, leaving their elderly parents and children at home. This threatens sustainable development at the family level. Because of the issues associated with the extreme conservation techniques such as planting trees through the Grain for Green program, policy makers are concerned whether any conservation cropping systems, such as some grass-crop rotation types between crop and trees, can be used balance the economic and environmental goals.

Lu et al. (2003) designed potential cropping systems for the Loess Plateau, and identified the resource-use-efficient cropping systems based on a simulation model. Their work suggests several cropping systems that can sustain agriculture from biophysical and agro-technological perspectives, but lacks economic evaluation. The purpose of this study is to add that economic perspective, including shadow pricing the abatement costs of agricultural pollutants. The abatement cost for a cropping system, estimated from a shadow pricing model described later, is the opportunity cost in terms of foregone crop revenue if environmental regulations were imposed. Policy makers are concerned about the abatement cost, since it provides an estimation of the cost imposed by the environmental regulations. But the abatement cost by itself is misleading in welfare analysis, since it captures the welfare loss only when farmers stay in the same cropping system. Farmers may respond to environmental regulations by switching to conservational cropping systems, which is associated with higher net profit. An environment-adjusted profit (EAP), defined based on the abatement cost in this study, can be used to assess cropping systems with different conservation techniques if environmental policies were implemented. The cropping systems that can bring high profit and meet the environmental requirements will be identified by a regression model. This study will provide the policy makers with an approach to appropriately estimate the costs imposed on farmers by environmental policies, as well as the cropping systems that can balance economic and environmental goals. The empirical example for the Loess Plateau provides an appropriate case study to investigate the approach, but the data are insufficient to make recommendations based on the findings herein.

The concept of a shadow price is very useful when non-marketed commodities or services need to be valued. Broadly speaking, there are two stakeholder positions that value unmarketable commodities or services. From the consumer side, most of the techniques are based on the fact that people do or will make trade-offs or sacrifices of other market goods or income in order to consume higher levels of environmental quality (Loomis, 2005). The travel cost method and the contingent valuation method are two examples (Champ *et al.*, 2003). The other approach is to look at the cost to reduce pollution. A producer-based distance function can be used to derive the shadow prices of pollutants, which provide an approximation of marginal abatement costs to producers. Abatement cost curve can be constructed when costs are plotted against contaminant levels. Instead of the value that consumers are willing to pay for the environmental services, a negative shadow price for an undesirable agricultural output reflects the marginal opportunity cost to farms of the restrictions on disposability of these undesirable outputs.

The distance function method developed by Färe et al. (1993), also called a shadow pricing model, can be used to derive revenue deflated shadow prices of undesirable outputs by applying a dual Shephard's lemma to the output distance function. Following this method, shadow prices of pollution from pulp and paper industry (Hailu and Veeman, 2000), and air pollution from electricity plants (Lee *et al.*, 2002; Färe *et al.*, 2005), have been estimated. Färe et al. (2006) later also estimated shadow prices of polluting outputs and the associated pollution costs for U.S. agriculture from 1960-96. In a related effort, Bond and Farzin (2007) shadow priced agricultural pollutants at plot level.

Building on previous research, this study will estimate the abatement costs and construct abatement cost curves for soil loss and agricultural pollutants in the Loess Plateau of China by Lu (2000), and evaluate the economic performance of alternative cropping systems when facing some environmental restrictions. Specifically, I employ a unique dataset including inputs and outputs from 1720 cropping systems in the Loess Plateau to measure shadow prices of two undesirable contaminants, i.e. soil and nitrogen. The abatement cost curves for soil and nitrogen are established. Environment-adjusted profit is defined by using abatement cost to evaluate the economic performance of the cropping systems if environmental policies were implemented. In Section 3.2, I describe the methodology in this study including shadow price estimation and contributions of alternative cropping systems to abatement costs and environment-adjusted profit.

The data is discussed in Section 3.3 and the empirical results in Section 3.4. Section 3.5 concludes and discusses the study.

3.2 Methodology

In this section, I first present the shadow pricing model developed by Färe et al. (1993), and its estimation techniques. The marginal abatement cost (MAC) and total abatement cost (TAC) curves for soil and nitrogen are estimated based on the shadow prices, respectively. Environment-adjusted profit (EAP) is defined by using the abatement costs to assess the economic performance of cropping systems if environmental regulations were imposed. Sequentially, a regression model is used to evaluate the contribution of alternative crop management practices to abatement costs and EAP.

3.2.1 Shadow Pricing Model and Its Estimation

I follow Färe et al. (2005) to present the shadow pricing model based on a directional output distance function. In the first step of this approach, the directional distance function, which underlies production technology, is constructed through an output possibility set. Then shadow prices of undesirable outputs are derived by setting the marginal rate of transformation between desirable and undesirable outputs equal to their price ratio. Finally, the estimation process of this model is presented.

3.2.1.1 The Directional Output Distance Function

The technologies for different cropping systems that produce desirable outputs and undesirable outputs jointly are represented by the output possibility set $\mathrm{P}(\mathbf{x}) = \{(\mathbf{y}, \mathbf{b}) : \mathbf{x} \text{ can produce } (\mathbf{y}, \mathbf{b})\}$, where $\mathbf{x} = (\mathrm{x}_1, \dots, \mathrm{x}_\mathrm{N}) \in \Re^\mathrm{N}_+$ is a vector of N inputs, $\mathbf{y} = (\mathrm{y}_1, \dots, \mathrm{y}_\mathrm{M}) \in \Re^\mathrm{M}_+$ is a vector of M desirable outputs and $\mathbf{b} = \left(\mathrm{b}_1, \dots, \mathrm{b}_\mathrm{J}\right) \in \Re^\mathrm{J}_+$ is a vector of J undesirable outputs. $\mathrm{P}(\mathbf{x})$ underlies all feasible input-output combinations. Standard assumptions are imposed on the output possibility set, including $\mathrm{P}(\mathbf{x})$ being compact and closed with $\mathrm{P}(\mathbf{0}) = \{0,0\}$, and inputs being freely disposed, i.e. $\mathbf{x'} \geq \mathbf{x}$ implied $\mathrm{P}(\mathbf{x'}) \supseteq \mathrm{P}(\mathbf{x})$. Free disposability of inputs means if inputs are increased, then the outputs will not shrink.

Two nonstandard assumptions on desirable and undesirable outputs are also imposed. First, desirable and undesirable outputs are weakly disposed, i.e. $(\mathbf{y}, \mathbf{b}) \in \mathrm{P}(\mathbf{x})$ and $0 \leq \theta \leq 1$ imply $(\theta\mathbf{y}, \theta\mathbf{b}) \in \mathrm{P}(\mathbf{x})$. This means that proportional reductions of desirable and undesirable outputs are feasible. Weak disposability allows for undesirable outputs to be deposed of at the cost of reductions in desirable outputs. Desirable outputs are not only weakly disposed but also freely disposed. Free disposability of desirable outputs means that desirable outputs can be disposed at no costs. The second nonstandard assumption on the technology is null-jointness, i.e. if $(\mathbf{y}, \mathbf{b}) \in \mathrm{P}(\mathbf{x})$ and $\mathbf{b} = 0$, then $\mathbf{y} = 0$. This means that undesirable outputs are inescapable if desirable outputs are produced.

Given the output possibility set $\mathrm{P}(\mathbf{x})$, the directional output distance function for the i^{th} observation $(\mathbf{x}_\mathrm{i}, \mathbf{y}_\mathrm{i}, \mathbf{b}_\mathrm{i})$ is defined as the simultaneous *maximum* reduction in bad outputs and expansion in good outputs along the direction represented by $\mathbf{g} = (\mathbf{g_y}, \mathbf{g_b})$. Its mathematical form is:

$$\mathrm{D_i}(\mathbf{x_i}, \mathbf{y_i}, \mathbf{b_i}; \mathbf{g_y}, \mathbf{g_b}) = \max\{\varphi_i > 0 : (\mathbf{y_i} + \boldsymbol{\varphi}_\mathbf{i}\mathbf{g_y}, \mathbf{b_i} + \boldsymbol{\varphi}_\mathbf{i}\mathbf{g_b}) \in \mathrm{P}(\mathbf{x_i})\}, \qquad \text{Equation 3.1}$$

where $\mathrm{D_i}$ is the distance function value for the ith observation $(\mathbf{x}_\mathrm{i}, \mathbf{y}_\mathrm{i}, \mathbf{b}_\mathrm{i})$ given the directional vector $(\mathbf{g_y}, \mathbf{g_b})$, and φ_i is the simultaneous change of desirable and undesirable outputs satisfying $(\mathbf{y_i} + \boldsymbol{\varphi}_\mathbf{i}\mathbf{g_y}, \mathbf{b_i} + \boldsymbol{\varphi}_\mathbf{i}\mathbf{g_b}) \in \mathrm{P}(\mathbf{x_i})$. The directional distance function is a measure of efficiency for the ith cropping system, representing the “distance” of the produced output bundle from the technically efficient production frontier along the directional vector $(\mathbf{g_y}, \mathbf{g_b})$. The production frontier is constructed by a set of cropping systems, whose distance function equals zero, i.e. $\mathrm{D_i}(\mathbf{x_i}, \mathbf{y_i}, \mathbf{z_i}; \mathbf{g_y}, \mathbf{g_b}) = 0$. This means that there is no possibility for these systems to reduce undesirable outputs and expand desirable outputs; therefore they are called efficient cropping systems.

Under the additional assumption of **g**-disposability[11], the output possibility set is equivalent to the directional output distance function (i.e. $(\mathbf{y}, \mathbf{b}) \in \mathrm{P}(\mathbf{x})$ if and only if $\mathrm{D_i}(\mathbf{x_i}, \mathbf{y_i}, \mathbf{b_i}; \mathbf{g_y}, -\mathbf{g_b}) \geq 0$). Thus, the production technology may be described by $\mathrm{P}(\mathbf{x})$, or equivalently, by $\mathrm{D}(\mathbf{x}, \mathbf{y}, \mathbf{b}; \mathbf{g}) \geq 0$. The **g**-disposability assumption also implies a translation property[12] for the distance function, i.e.

$$\mathrm{D}(\mathbf{x}, \mathbf{y} + \varphi\mathbf{g_y}, \mathbf{b} + \varphi\mathbf{g_b}; \mathbf{g_y}, \mathbf{g_b}) = \mathrm{D}(\mathbf{x}, \mathbf{y}, \mathbf{b}; \mathbf{g_y}, \mathbf{g_b}) - \varphi. \qquad \text{Equation 3.2}$$

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[11] **g**-disposability implies if $(\mathbf{y}, \mathbf{b}) \in \mathrm{P}(\mathbf{x})$ then $(\mathbf{y} + \varphi\mathbf{g_y}, \mathbf{b} + \varphi\mathbf{g_b}) \in \mathrm{P}(\mathbf{x})$.

[12] The translation property says if the desirable output is expanded by $\varphi\mathbf{g_y}$ and undesirable output is contracted by $\varphi\mathbf{g_b}$, the resulting distance function value will be reduced by φ, and therefore its efficiency will be improved by φ.

Corresponding to the assumptions imposed on the output possibility set, the directional output distance function has the following properties.

(1) $D_i(\mathbf{x}_i, \mathbf{y}_i, \mathbf{b}_i; \mathbf{g}_\mathbf{y}, \mathbf{g}_\mathbf{b}) \geq 0$ if and only if $(\mathbf{y}_i, \mathbf{b}_i)$ is an element of $P(\mathbf{x})$.

(2) $D_i(\mathbf{x}_i, \mathbf{y}'_i, \mathbf{b}_i; \mathbf{g}_\mathbf{y}, \mathbf{g}_\mathbf{b}) \geq D_i(\mathbf{x}_i, \mathbf{y}_i, \mathbf{b}_i; \mathbf{g}_\mathbf{y}, \mathbf{g}_\mathbf{b})$ for $(\mathbf{y}'_i, \mathbf{b}_i) \leq (\mathbf{y}_i, \mathbf{b}_i)$.

(3) $D_i(\mathbf{x}_i, \mathbf{y}_i, b'_i; \mathbf{g}_\mathbf{y}, \mathbf{g}_\mathbf{b}) \geq D_i(\mathbf{x}_i, \mathbf{y}_i, \mathbf{b}_i; \mathbf{g}_\mathbf{y}, \mathbf{g}_\mathbf{b})$ for $(\mathbf{y}_\mathbf{i}, \mathbf{b}_\mathbf{i}) \geq (\mathbf{y}_\mathbf{i}, \mathbf{b'}_\mathbf{i})$.

(4) $D_i(\mathbf{x}_i, \theta\mathbf{y}_i, \theta\mathbf{b}_i; \mathbf{g}_\mathbf{y}, \mathbf{g}_\mathbf{b}) \geq 0$ for $(\mathbf{y}_\mathbf{i}, \mathbf{b}_\mathbf{i}) \in P(\mathbf{x})$ and $0 \leq \theta \leq 1$.

(5) $D(\mathbf{x}, \mathbf{y}, \mathbf{b}; \mathbf{g}_\mathbf{y}, \mathbf{g}_\mathbf{b})$ is concave in $(\mathbf{y}, \mathbf{b}) \in P(\mathbf{x})$.

(6) $D_i(\mathbf{x}, \mathbf{y} + \varphi\mathbf{g}_\mathbf{y}, \mathbf{b} - \varphi\mathbf{g}_\mathbf{b}; \mathbf{g}_\mathbf{y}, \mathbf{g}_\mathbf{b}) = D_i(\mathbf{x}, \mathbf{y}, \mathbf{b}; \mathbf{g}_\mathbf{y}, \mathbf{g}_\mathbf{b}) - \varphi$.

The directional output distance function under these assumptions is illustrated in Figure 3.1. The dots represent a sample of all the observations that construct the output possibility set $P(x)$. The output possibility set is encompassed by the Pareto efficient frontier (i.e. the curve in Figure 3.1) and the horizontal axis. The observations beneath the frontier are inefficient and their distance functions are greater than zero (for example, the observation denoted by(b, y). The observations on the frontier are efficient and their corresponding distance functions equal zero. The arrows denote the directional vector (g_b, g_y), along which an inefficient observation can improve its efficiency by increasing desirable output and reducing undesirable output. For example, the efficiency of the observation (b, y) can be improved by moving from (b, y) to point E along the directional vector. The coordinate of point E is $(b + \varphi g_b, y + \varphi g_y)$.

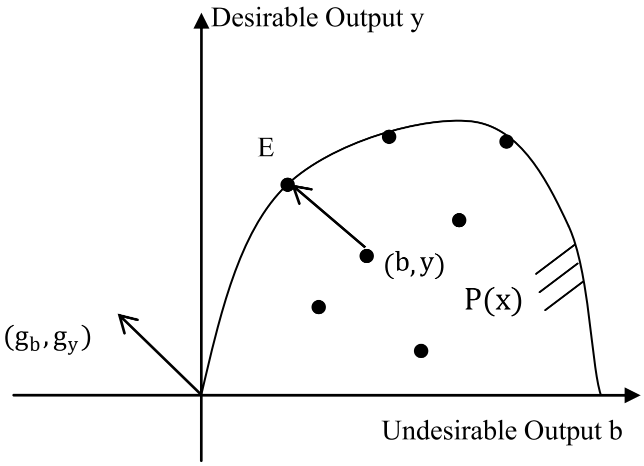

Figure 3.1. The Directional Output Distance Function

Note: The dots are a sample of all observations that construct the output possibility set P(x). The curve is the Pareto efficient frontier established by all efficient observations. The arrows denote the directional vector(g_b, g_y). All the dots under the frontier curve are inefficient, for example, (b, y). The distance function measures the efficiency. For example, the value of distance function for (b, y) is the "distance" from point (b, y) to point E along the arrow direction.

3.2.1.2 Shadow Price Derivation

To derive the shadow prices, it is necessary to examine the relationship between the maximal revenue function and the directional distance function (Färe *et al.*, 2006). Let $\mathbf{p_y} = (p_{y1}, \dots p_{yM}) \in \Re_+^M$ represent desirable output prices and let $\mathbf{p_b} = (p_{b1}, \dots, p_{bJ}) \in \Re_-^J$ represent undesirable output prices. The revenue function, which considers the negative effect generated by the undesirable outputs, is defined as:

$$R_i(\mathbf{x_i}, \mathbf{p_y}, \mathbf{p_b}) = \max_{\mathbf{y},\mathbf{b}}\{\mathbf{p_y}\mathbf{y_i} + \mathbf{p_b}\mathbf{b_i} \colon (\mathbf{y}, \mathbf{b}) \in P(\mathbf{x})\}. \qquad \text{Equation 3.3}$$

The revenue function gives the maximal revenue that can be generated from inputs **x** under the technology constraint, when desirable output prices are $\mathbf{p_y}$ and undesirable output prices are $\mathbf{p_b}$.

Since $(\mathbf{y}, \mathbf{b}) \in \mathrm{P}(\mathbf{x})$ implies $\mathrm{D}_{\mathrm{i}}(\mathbf{x}_{\mathrm{i}}, \mathbf{y}_{\mathrm{i}}, \mathbf{b}_{\mathrm{i}}; \mathbf{g_y}, \mathbf{g_b}) \geq 0$, the maximal revenue function can be equivalently written as[13]:

$$\mathrm{R}_{\mathrm{i}}(\mathbf{x}_{\mathrm{i}}, \mathbf{p_y}, \mathbf{p_b}) = \max_{\mathbf{y},\mathbf{b}}\{\mathbf{p_y y_i} + \mathbf{p_b b_i}\!: \mathrm{D}_{\mathrm{i}}(\mathbf{x_i}, \mathbf{y_i}, \mathbf{b_i}; \mathbf{g_y}, \mathbf{g_b}) \geq 0\}. \qquad \text{Equation 3.4}$$

To solve this equation, it is written as:

$$\mathrm{R}_{\mathrm{i}}(\mathbf{x_i}, \mathbf{p_y}, \mathbf{p_b}) \geq (\mathbf{p_y}, \mathbf{p_b})(\mathbf{y} + \mathrm{D}_{\mathrm{i}}(\mathbf{x_i}, \mathbf{y_i}, \mathbf{b_i}; \mathbf{g_y}, \mathbf{g_b})\mathbf{g_y}, \mathbf{b} + \mathrm{D}_{\mathrm{i}}(\mathbf{x_i}, \mathbf{y_i}, \mathbf{b_i}; \mathbf{g_y}, \mathbf{g_b})\mathbf{g_b})$$

$$= (\mathbf{p_y y} + \mathbf{p_b b}) + (\mathbf{p_y}\mathrm{D}_{\mathrm{i}}(\mathbf{x}, \mathbf{y}, \mathbf{b}; \mathbf{g})\mathbf{g_y} + \mathbf{p_b}\mathrm{D}_{\mathrm{i}}(\mathbf{x}, \mathbf{y}, \mathbf{b}; \mathbf{g})\mathbf{g_b}). \qquad \text{Equation 3.5}$$

Rearranging the above inequality, the directional distance function can be written as:

$$\mathrm{D}(\mathbf{x}, \mathbf{y}, \mathbf{b}; \mathbf{g}) \leq \frac{\mathrm{R}_{\mathrm{i}}(\mathbf{x_i}, \mathbf{p_y}, \mathbf{p_b}) - (\mathbf{p_y y} + \mathbf{p_b b})}{\mathrm{p_y g_y} + \mathrm{p_b g_b}},$$

Equation 3.6

which yields:

$$\mathrm{D}_{\mathrm{i}}(\mathbf{x}, \mathbf{y}, \mathbf{b}; \mathbf{g}) = \min_{\mathbf{p}}\left\{\frac{\mathrm{R}(\mathbf{x}, \mathbf{p_y}, \mathbf{p_b}) - (\mathbf{p_y y} + \mathbf{p_b b})}{\mathbf{p_y g_y} + \mathbf{p_b g_b}}\right\}.$$

Equation3.7

Applying the envelope theorem yields the shadow price model:

$$\nabla_{\mathrm{b}}\mathrm{D}(\mathbf{x}, \mathbf{y}, \mathbf{b}; \mathbf{g}) = \frac{-\mathrm{p_b}}{\mathrm{p_y g_y} + \mathrm{p_b g_b}} \geq 0$$

Equation 3.8

and

$$\nabla_{\mathrm{y}}\mathrm{D}(\mathbf{x}, \mathbf{y}, \mathbf{b}; \mathbf{g}) = \frac{-\mathrm{p_y}}{\mathrm{p_b g_y} + \mathrm{p_b g_b}} \leq 0.$$

---

[13] The maximal revenue must be associated with the cropping systems after their inefficiencies are eliminated.

Equation 3.9

Thus, given the mth desirable output price, say p_{ym}, the shadow price of the jth undesirable output can be recovered by taking the ratio of Equation 3.8 and Equation 3.9:

$$\frac{p_{bj}}{p_{ym}} = \frac{\partial D(\mathbf{x}, \mathbf{y}, \mathbf{b}) / \partial b_j}{\partial D(\mathbf{x}, \mathbf{y}, \mathbf{b}) / \partial y_m}$$

or

$$p_{bj} = p_{ym} \left(\frac{\partial D(\mathbf{x}, \mathbf{y}, \mathbf{b}) / \partial b_j}{\partial D(\mathbf{x}, \mathbf{y}, \mathbf{b}) / \partial y_m}\right).$$

Equation 3.10

So far, I have derived the shadow prices for the undesirable outputs. Equation 8 implies that revenue is maximized where the marginal rate of transformation between an undesirable output and a desirable output equals their price ratio.

The negative shadow prices of undesirable outputs, derived by a directional distance function, are interpreted as marginal opportunity costs in terms of revenue foregone (Färe *et al.*, 2006). They also provide an estimate of marginal abatement costs of agricultural pollutants to *farmers*. MAC curves can be constructed by plotting the shadow prices against the levels of corresponding undesirable output.

3.2.1.3 Estimation of Distance Function

The shadow pricing model, derived in the previous section, provides a conceptual way to estimate shadow prices of the undesirable outputs. A necessary step to implement this model is to parameterize the distance function, since the derivatives of the distance function are utilized

(Equation 3.8). A linear programming technique is employed to calibrate the unknown parameters in the distance function. A regular regression technique is not appropriate here, because the values of the distance function are unavailable before estimation.

Among the flexible functional forms, a deterministic quadratic function is chosen to parameterize the directional distance function. A quadratic functional form can be restricted to satisfy the translation property (Färe *et al.*, 2005) while a translog functional form, for example, cannot. I choose $\mathbf{g} = (\mathbf{1}, -\mathbf{1})$ as a directional vector, where the first M components equal 1 and the next J components equal -1. This means that the same proportion of reduction in undesirable outputs and expansion in desirable outputs will bring the inefficient observation to the frontier. Assuming $\mathrm{i} = 1, \ldots, \mathrm{I}$ cropping systems, the quadratic directional distance function for the i^{th} cropping system is:

$$\begin{aligned} D^{i}(\mathbf{x_i}, \mathbf{y_i}, \mathbf{b_i}; \mathbf{1}, -\mathbf{1}) &= \alpha_0 + \sum_{n=1}^{N} \alpha_n x_n^i + \sum_{m=1}^{M} \beta_m y_m^i + \sum_{j=1}^{J} \gamma_j b_j^i \\ &+ \frac{1}{2} \sum_{n=1}^{N} \sum_{n'=1}^{N} \alpha_{nn'} x_n^i x_{n'}^i + \frac{1}{2} \sum_{m=1}^{M} \sum_{m'=1}^{M} \beta_{mm'} y_m^i y_{m'}^i + \frac{1}{2} \sum_{j=1}^{J} \sum_{j'=1}^{J} \gamma_{jj'} b_j^i b_{j'}^i \\ &+ \sum_{n=1}^{N} \sum_{m=1}^{M} \delta_{nm} x_n^i y_m^i + \sum_{n=1}^{N} \sum_{j=1}^{J} \eta_{nj} x_n^i b_j^i + \sum_{m=1}^{M} \sum_{j=1}^{J} \mu_{mj} y_m^i b_j^i, \end{aligned}$$

Equation 3.11

where $D^{i}(\mathbf{x_i}, \mathbf{y_i}, \mathbf{b_i}; \mathbf{1}, -\mathbf{1})$ is the value of distance function for the i^{th} cropping system which use inputs $\mathbf{x_i}$ to produce outputs $(\mathbf{y_i}, \mathbf{b_i})$ given the directional vector $(\mathbf{1}, -\mathbf{1})$; x_n^i is the n^{th} input of the i^{th} cropping system, $n = 1, \ldots, N$; y_m^i is the m^{th} desirable output of the i^{th} cropping system, $m = 1, \ldots, M$; b_j^i is the j^{th} undesirable output of the i^{th} cropping system, $j = 1, \ldots, J$;

$\alpha_0, \alpha_n, \beta_m, \gamma_j, \alpha_{nn'}, \beta_{mm'}, \gamma_{jj'}, \delta_{nm}, \eta_{nj}$, μ_{mj} are unknown parameters. Constraints on the parameters should be imposed to satisfy the properties of the distance function when estimating this quadratic function. Symmetry of the cross-output and cross-input effects is also assumed, and requires $\alpha_{nn'} = \alpha_{n'n}$ for $n \neq n'$; $\beta_{mm'} = \beta_{m'm}$ for $m \neq m'$; $\gamma_{jj'} \neq \gamma_{j'j}$ for $j \neq j'$.

A linear programming technique is used to estimate the unknown parameters in the quadratic distance function following the work of Aigner and Chu (1968), which is also used by Färe et al.(2005; 2006). Specifically, the parameters in Equation 3.11 are estimated by minimizing the sum of the distances between the frontier technology and each individual observation, subject to the constraints implied by the distance function properties. This can be written into a linear programming form as follows:

$$\min_{\beta} \sum_{i=1}^{I} [D_i(x, y, b; 1, -1) - 0]$$

Equation 3.12

subject to:

$$D_i(x, y, b; 1, -1) \geq 0, i = 1, \dots, I \qquad \text{Eq. 3.12(a)}$$

$$\frac{\partial D_i(x, y, b; 1, -1)}{\partial b_j} \geq 0, i = 1, \dots, I, j = 1, \dots, J \qquad \text{Eq. 3.12(b)}$$

$$\frac{\partial D_i(x, y, b; 1, -1)}{\partial y_m} \leq 0, i = 1, \dots, I, m = 1, \dots, M \qquad \text{Eq. 3.12(c)}$$

$$\frac{\partial D_i(x, y, b; 1, -1)}{\partial x_n} \geq 0, i = 1, \dots, I, n = 1, \dots, N \qquad \text{Eq. 3.12(d)}$$

$$\sum_{m=1}^{M} \beta_m - \sum_{j=1}^{J} \gamma_j = -1, \sum_{m'=1}^{M} \beta_{mm'} - \sum_{j=1}^{J} \mu_{mj} = 0, m = 1, \dots, M \qquad \text{Eq. 3.12(e)}$$

$$\sum_{j'=1}^{J}\gamma_{jj'} - \sum_{m=1}^{M}\mu_{mj} = 0, j = 1, \dots, J \qquad \text{Eq. 3.12(f)}$$

$$\sum_{m=1}^{M}\delta_{nm} - \sum_{j=1}^{J}\eta_{nj} = 0, n = 1, \dots, N \qquad \text{Eq. 3.12(g)}$$

$$\alpha_{nn'} = \alpha_{n'n} \text{ for } n \neq n';\ \beta_{mm'} = \beta_{m'm} \text{ for } m \neq m'; \gamma_{jj'} \neq \gamma_{j'j} \text{ for } j \neq j'. \qquad \text{Eq. 3.12(h)}$$

3.2.2 Contribution of Crop Management Alternatives

Policy makers are concerned about the cost of an environmental policy on farmers. They also care about the economic performance of alternative cropping systems if environmental regulations were implemented. Environment-adjusted profit (EAP) is defined as profit without environmental regulations minus the abatement costs. EAP can be used to assess the economic performance if environmental regulations were imposed. It also can be used to identify the tradeoff between profitability and environmental restrictions. A regression analysis of EAP on the characters of cropping systems can identify the contributions of cropping practice alternatives. Farmers can switch to the most profitable cropping systems when facing environmental restrictions with the assistance of this information.

I will first introduce the key terms in the regression model. Given the shadow prices estimated from the shadow pricing model in Section 3.2.1, the MAC curves can be plotted in a quantity-price dimension. Assuming the MAC curve is increasing and convex (Figure 3.2), if a pollutant cap is set at b*, the total abatement cost for a cropping system to reduce the pollutant from b to b* can be calculated by measuring the shaded area under the MAC curve.

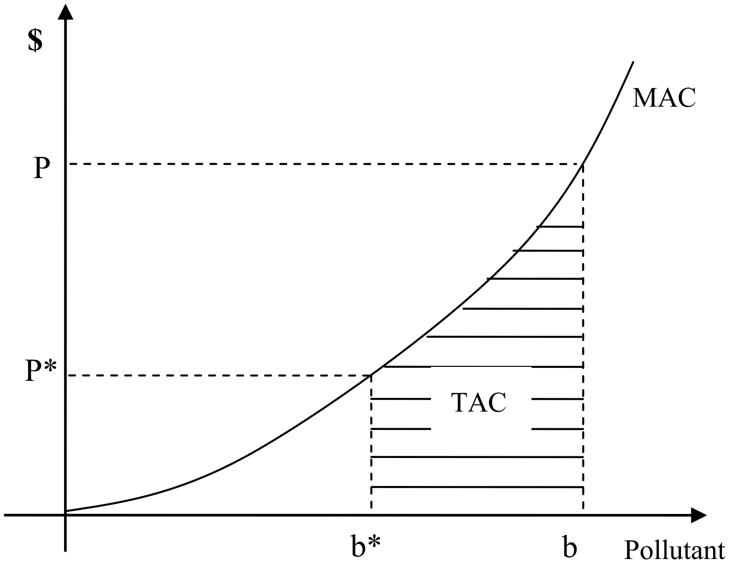

Figure3.2. Marginal Abatement Cost and Total Abatement Cost

Profit is reduced by compliance to an environmental limit. Environment-adjusted profit (EFP) is an important indicator in evaluating the impact of environmental regulations on farm profit. It is defined as a farms' net profit when environmental regulations are imposed, and measured by subtracting total abatement costs (TAC) from their financial profit (π_F). Mathematically, it is written as:

$$\mathrm{EFP} = \pi_F - \mathrm{TAC}. \qquad \text{Equation 3.13}$$

The impact of a limiting environmental policy on farm profit is illustrated in Figure 3.3. The output possibility set and the Pareto efficient curve like that shown in Figure 3.1 is given in the southeast quadrant. The profits curve without any environmental policy imposed, denoted by π_F, is drawn in the northwest quadrant. Assuming no pollution allowed in this example, the TAC curve is given in northeast quadrant. If an environmental policy was implemented, the farm will lose some profit by the amount of the total abatement cost. The profit curve with the environmental policy imposed, denoted by EFP, is therefore derived, and shown in the northwest quadrant. The maximal profit without the environmental regulations is π_F^*, and its corresponding crop yield is y_F^*. The maximal profit with environmental regulations is EAP*, and its corresponding crop yield is y_E^*.

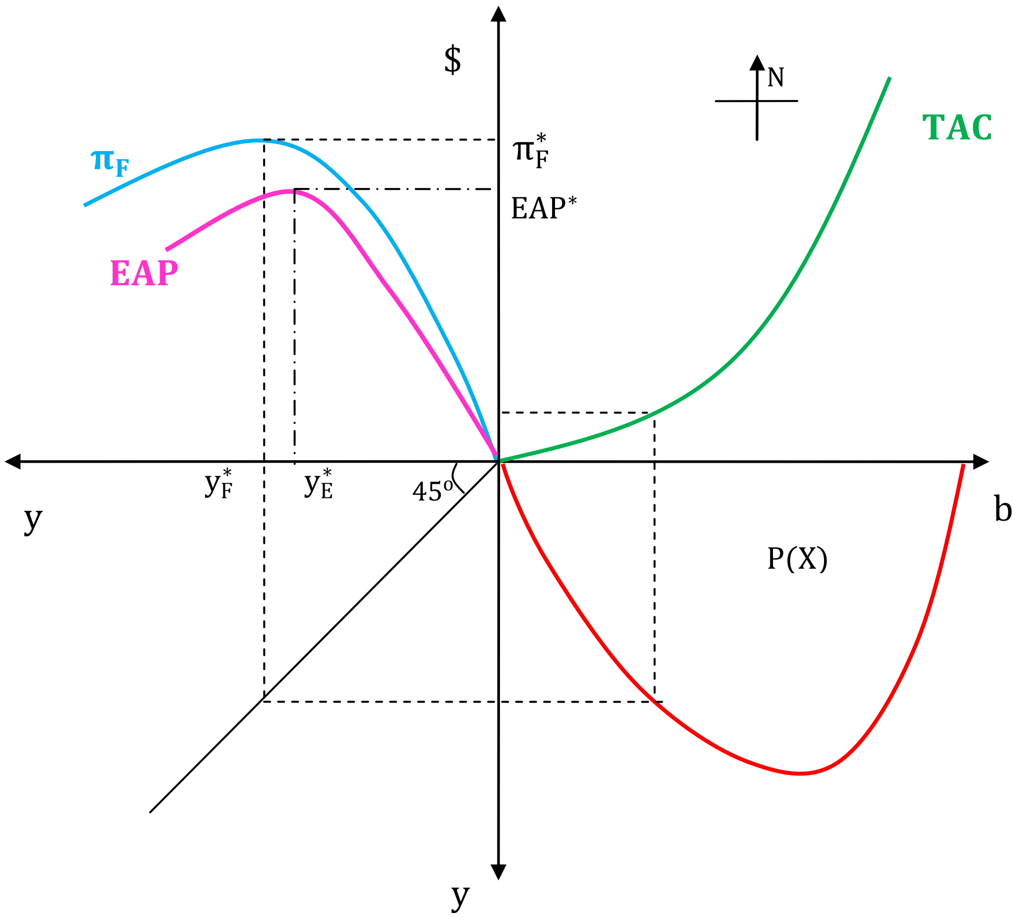

Figure3.3. The TAC and Profit Curves

Note: y is a desirable output; b is a pollutant. P(x) is the output possibility set. TAC denotes the total abatement cost curve, assuming no pollution allowed; π_F denotes the profit curve without any environmental policy imposed; EAP denotes the profit curve with an environmental regulation, which is derived.

Different farms employ alternative cropping systems, characterized by crop management, conservation techniques and production situations, etc. Marginal contribution of conservation practice alternatives can be analyzed through a regression model as follows:

$$\mathrm{Y_i} = \beta_0 + \boldsymbol{\beta_1}\mathbf{ROT_i} + \boldsymbol{\beta_2}\mathbf{RES_i} + \boldsymbol{\beta_3}\mathbf{CONT_i} + \boldsymbol{\beta_4}\mathbf{PRO_i} + \boldsymbol{\beta_5}\mathbf{MEC_i}$$

$$+\boldsymbol{\beta_6}\mathbf{TER_i} + \boldsymbol{\beta_7}\mathbf{SLP_i} + \varepsilon_i \qquad \text{Equation 3.14}$$

where $\mathrm{Y_i}$ is the total abatement cost for the $\mathrm{i^{th}}$ cropping system when facing some environmental regulation (the TAC model) or the environment-adjusted farm profit (the EAP model); $\mathbf{ROT_i}$ is a set of dummy variables for crop rotation types, $\mathbf{RES_i}$ for crop residue management, $\mathbf{CONT_i}$ for contour or furrow ridging, $\mathbf{PRO_i}$ for production situations, $\mathbf{MEC_i}$ for mechanization levels, $\mathbf{TER_i}$ for terracing techniques and $\mathbf{SLP_i}$ for land steepness. All βs are parameters to be estimated. ε_i is the error term.

3.3 Data

Research on the estimation of shadow prices of agricultural pollutants by the shadow pricing model is limited, since non-point agricultural pollution is difficult to measure directly. Färe et al. (2006) employed two indices, which capture the effect of pesticide leaching and runoff on drinking water and surface water, to approximate the undesirable outputs from chemical use for the US 48 continuous states from 1960-96. An analysis using the aggregate input-output data can provide an overview of the abatement costs of agricultural pollution at the state level. But it will be misleading for a specific watershed or field. Bond and Farzin (2007) estimated the abatement costs at the plot level, but had to approximate undesirable outputs by number of field trips and amount of pesticide inputs.

This chapter employs the simulation data from the Environmental Policy Integrated Climate (EPIC) model, validated with the experimental data in Ansai County of the Loess Plateau by Lu (2000). This dataset has at least three advantages over the data used in previous studies. First, agricultural pollutants such as nitrogen loss and soil erosion are measured directly in their absolute units instead of approximate indices. Second, all potential cropping systems can be simulated, while only limited cropping systems can be observed at the farm level. Third, simulation data makes the estimation of the shadow prices of agricultural pollutants more accurate, since the inefficiencies and differences caused by farm characteristics and measurement errors are eliminated.

The EPIC model is a comprehensive simulation model that can predict the effects of various management decisions on soil, water, nutrient and pesticide movements and their combined impact on soil loss, water quality and crop yield (Williams *et al.*, 2006). It consists of weather, water and wind erosion, nitrogen leaching, pesticide fate and transport, crop growth and yield, crop rotations, tillage, plant environment control (drainage, irrigation, fertilization, furrow diking, liming), economic accounting, waste management, etc. In the Lu (2000) study, 2006 cropping systems were specified based on six design categories including 5 land units, 17 crop rotation types, 3 production situations, 2 tillage techniques, 2 crop residue management techniques and 2 mechanization levels (Table 3.1).

Table 3.1. Cropping Systems Identified and Measured by Lu (2000)

Categories	Specifications
Land Units	**5** units classified by land slope steepness: floodplains, gently steeply sloped land, moderately steeply sloped land, steeply sloped land, and very steeply sloped land
Crop rotations[a]	**2** mono crops: C and W **8** types of rotation without alfalfa: PsWC, CMPa, CSC, FWPaM, PsWCM, MSC, WPaMCF, MSMPa **7** types of rotation with alfalfa: A3CM, A3CPaM, A3MPaM, A4MPaM, FA5MC, FWA4MC, A3MCPaCM
Production situations	**3** situations with different availability of water and nutrients: sufficient water and nitrogen, water-limited and nitrogen-limited
Conservation Techniques	**4** techniques: contouring + mulching, contouring + non-mulching, furrow-ridging + mulching, furrow-ridging + non-mulching.
Mechanization	**2** levels: human and animal labor, semi-mechanization

a-A#=alfalfa and years, C=corn, M=millet, F=flax, Ps=Summer Potato, Pa=Autumn Potato, S=soybean, W=winter wheat

To implement the shadow pricing model, I include seeds, nutrients (N, P and K), biocides, irrigation if applicable, farm equipment, labor, animal traction and tractors as inputs, crop yield and two agricultural contaminants as outputs, in my production set. Because eight inputs are used and eight crops are produced in some cropping systems, input prices and output prices (Table 3.2) are used as weights to create output index and input index.

Table 3.2. Input and Output Prices Used to Calculate Total Revenue and Total Costs

Input Name	Input Price	Unit[a]	Output Name	Output Price	Unit[a]
Nitrogen (N)	2.9	RMB/kg	Corn	1.24	RMB/kg
Phosphorus (P)	7.8	RMB/kg	Millet	1.28	RMB/kg
Potassium(K)	4.8	RMB/kg	Wheat	1.40	RMB/kg
Biocide	40.0	RMB/kg	Soybean	2.40	RMB/kg
Human Labor	10.0	RMB/day	Autumn Potato	0.60	RMB/kg
Oxen Labor	20.0	RMB/day	Summer Potato	0.90	RMB/kg
Donkey Labor	15.0	RMB/day	Flax	1.68	RMB/kg
-	-	-	Alfalfa	0.60	RMB/kg

Source: Lu (2000)

a-1 US dollar = 6.3 RMB at year 2012

The condition of null-jointness between desirable outputs and undesirable outputs implies that no crop can be produced without any nitrogen loss or soil loss. I drop 266 cropping systems with zero soil loss and end up with 1720 observations. Descriptive statistics for the inputs and outputs used in estimating the distance function are given in Table 3.3. The means of total cost and total revenue are 3059 and 5240 RMB/ha for the 1720 cropping systems. The means of nitrogen loss and soil loss are 15.6 kg/ha and 3.6 t/ha, respectively.

Table 3.3. Descriptive Statistics of the Variables Used in the Distance Function [a]

Variable	Mean	Standard Deviation	Minimum	Maximum
Total Cost (RMB/ha)[b]	3059	591.1	1426	4910
Total Revenue (RMB/ha)[c]	5240	1536.5	1446	12594
Nitrogen Loss (kg/ha)	15.6	9.4	0.01	57.6
Soil Loss (kg/ha)	3629	7961	0.5	69838

a-1 US dollar = 6.3 RMB at year 2012; b. input index; c. output index.

3.4 Empirical Results

3.4.1 Distance Function Values and Shadow Prices

To ensure the estimation of the parameters stay in the reasonable scale, I normalize each output and input by their mean value. The parameters in the quadratic functional form of the distance function were estimated by the linear programming technique described later; the results are provided in Table 3.4. For example, the coefficient α_1 in front of the variable x_1 is equal to 0.1358. There is no interesting economic interpretation of these coefficients, but they can be used to calculate the distance function values and shadow prices.

By plugging the estimated parameters into the distance function of the quadratic functional form (Equation 3.11), together with total cost, total revenue, soil loss and nitrogen loss, the distance function values for each cropping system can be calculated. Utilizing Equation 3.8, the shadow prices of soil loss and nitrogen loss are estimated.

Table 3.4. Estimated Coefficients in the Quadratic Distance Function

Coefficient	Variable[a]	Estimate
α_0	Intercept	1.0397
α_1	x_1	0.1358
β_1	y_1	-0.9660
γ_1	b_1	0.1201
γ_2	b_2	-0.0861
α_{11}	$1/2x_1^2$	-0.1207
β_{11}	$1/2y_1^2$	0.0791
γ_{11}	$1/2b_1^2$	0.0740
γ_{22}	$1/2b_2^2$	0.0045
$\gamma_{12} = \gamma_{21}$	$b_1 b_2$	0.0003
δ_{11}	$x_1 y_1$	0.0223
η_{11}	$x_1 b_1$	0.0253
η_{12}	$x_1 b_2$	-0.0029
μ_{11}	$y_1 b_1$	0.0743
μ_{12}	$y_1 b_2$	0.0048

a-x_1 is the ith total cost divided by the average total cost; y_1 is the ith total revenue divided by the average total revenue; b_1 is the ith nitrogen loss divided by the average nitrogen loss; b_2 is the ith soil loss divided by the average soil loss.

Descriptive statistics of the distance function values and shadow prices are given in Table 3.5. The mean of the distance function values for 1720 cropping systems is 0.414. Since I estimate the distance function using normalized data, the mean 0.414 is interpreted as: the average cropping system will be on the frontier if crop revenue is increased by 2169 RMB/ha (0.414*5240RMB/ha), nitrogen loss decreased by 6.46 kg/ha (0.414*15.6 kg/ha), and soil loss decreased by 1.5 ton/ha (0.414*3629 kg/ha)[14] The mean of shadow prices of soil loss and nitrogen loss are -0.102 RMB/kg and -0.383 RMB/kg, respectively. It implies the marginal abatement cost for soil loss is 0.102 RMB/kg; 0.383RMB/kg for nitrogen loss.

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[14] The means of crop revenue, nitrogen loss and soil loss is reported in Table 3.2.

Table 3.5. Descriptive Statistics of Distance Function Values and Shadow Prices

Variable	Mean	Standard Deviation	Minimum	Maximum
Distance Function Value	0.414	0.217	0	1.164
Shadow Price of Soil Loss (RMB/kg)[a]	-0.102	0.014	-0.162	0
Shadow Price of Nitrogen Loss (RMB/kg)	-0.383	0.116	-1.291	-0.210

a-1 US dollar = 6.3RMB at year 2012

Histograms of the distance function values and shadow prices of soil loss and nitrogen loss are given in Figures 3.4-3.6. The distance function values range from 0 to about 1.2, most of which lie between 0 and 0.8. Shadow prices of soil loss and nitrogen loss have a range from 0 to 0.162 RMB/kg and from 0.21 to 1.29 RMB/kg, respectively. However, over 90% cropping systems have the shadow price of soil loss between 0.08 and 0.12 RMB/kg; the shadow price of nitrogen loss lies between 0.2 and 0.5 RMB/kg for over 90% cropping systems.

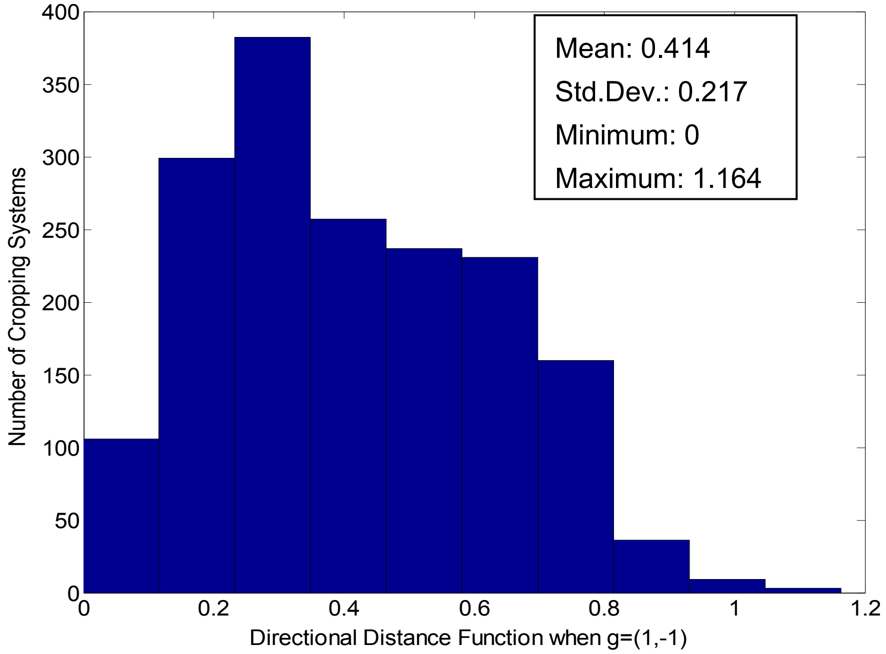

Figure 3.4. Histogram of Directional Distance Function for 1720 Cropping Systems

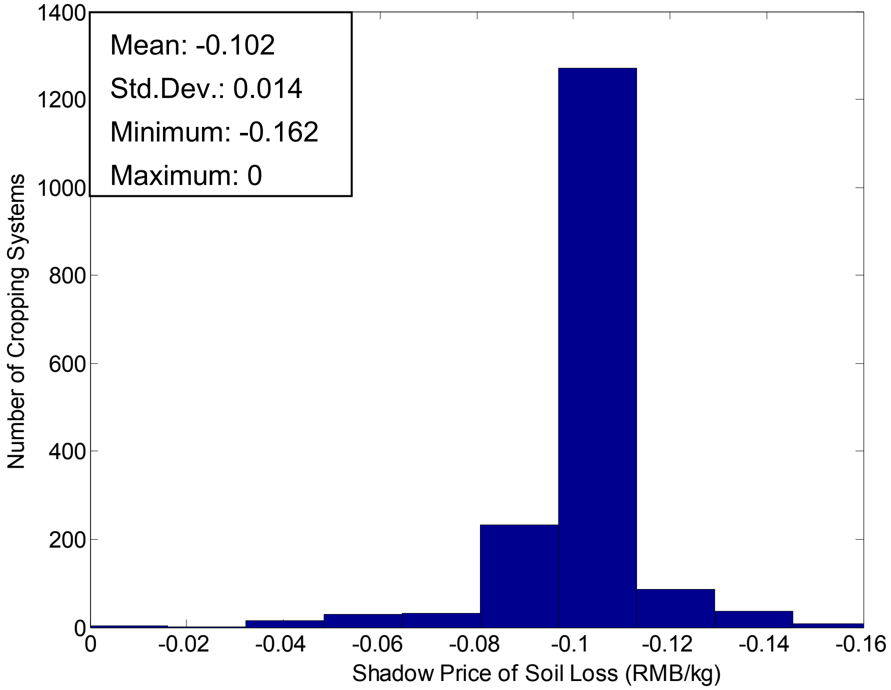

Figure 3.5. Histogram of Shadow Price of Soil Loss for 1720 Cropping Systems

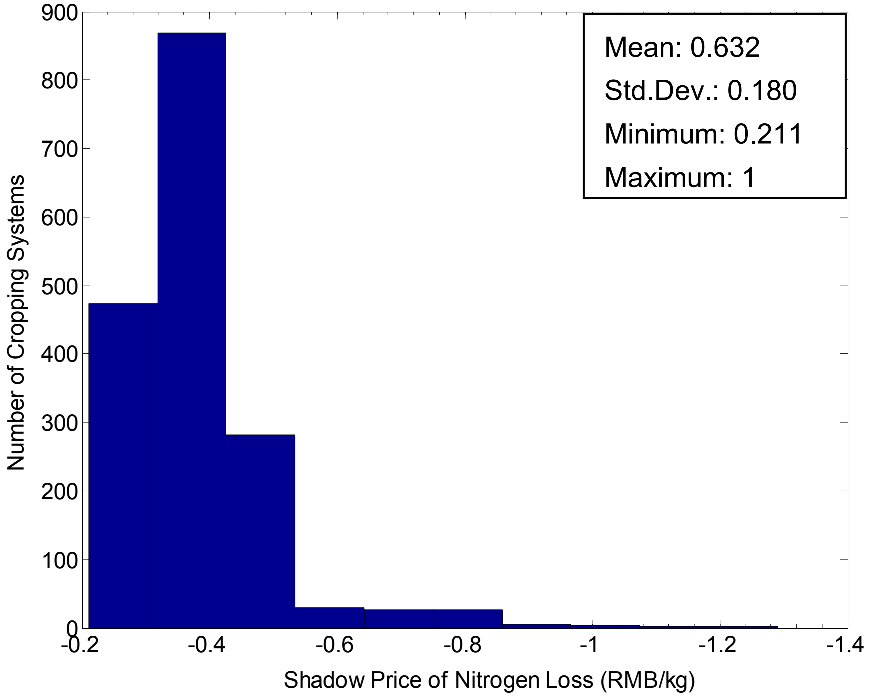

Figure 3.6. Histogram of Shadow Price of Nitrogen Loss for 1720 Cropping Systems

3.4.2 Marginal and Total Abatement Costs

The shadow price of agricultural pollutant estimated by the distance function approach can be interpreted as the foregone revenue to farmers when the marginal agricultural pollutant has to be reduced. It provides an estimate of the marginal abatement cost (MAC). I estimated the MAC curves for all 1720 cropping systems, as well as for the dominant cropping systems. The dominant cropping systems are those with the least marginal abatement cost given the amount of agricultural pollution.

The MAC curves for soil loss (Figure 3.7) are downward sloping, while the MAC curves for nitrogen loss (Figure 3.8) are upward sloping. This is because low crop yield is associated with high levels of soil loss, but high crop yield is correlated with high nitrogen loss. The marginal abatement cost for soil is estimated to be linear to its level for both dominant cropping systems and all cropping systems, while a quadratic relationship exist for nitrogen. These curves were used to trace out the total abatement cost (TAC) curves.

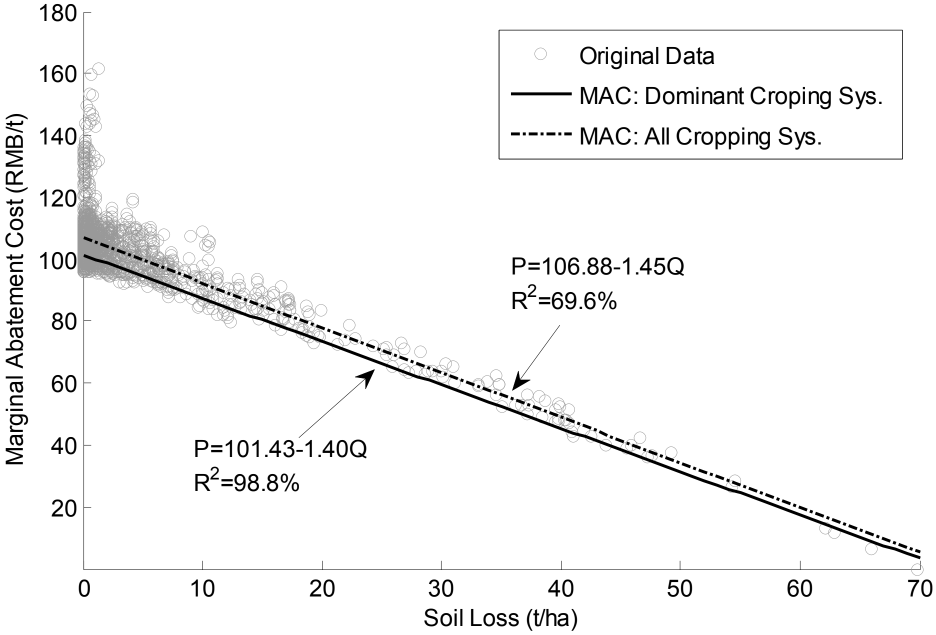

Figure 3.7. Marginal Abatement Cost for Soil Loss

Note: P = Shadow Price of Soil Loss, Q= Soil Loss

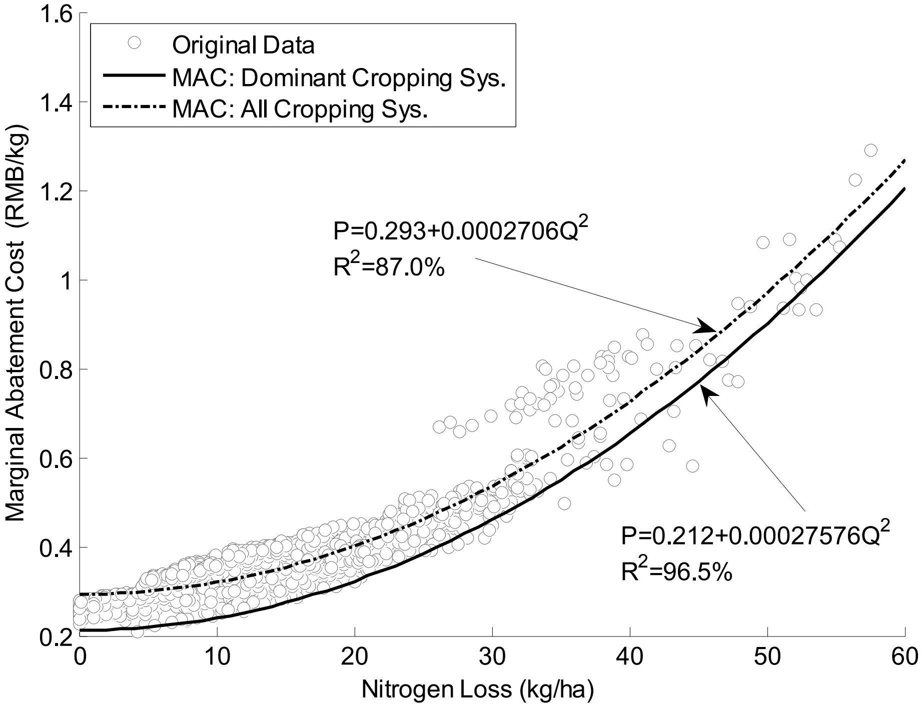

Figure 3.8. Marginal Abatement Cost for Nitrogen Loss

Note: P = Shadow Price of Nitrogen Loss; Q = Nitrogen Loss.

The total abatement cost (TAC) curves and functions for soil loss are given in Figure 3.9. The TAC curve for soil loss of dominant cropping systems is beneath that of all cropping systems. Both are increasing and concave. As soil loss goes up, total abatement cost is increasing at a decreasing rate. The total abatement cost (TAC) curves and functions for nitrogen loss are given in Figure 3.10. The TAC curve for nitrogen of the dominant systems lies below the one for all cropping systems. Both are increasing, but different from TAC for soil, they are convex. The total abatement cost goes up at an increasing rate as the level of nitrogen loss increases.

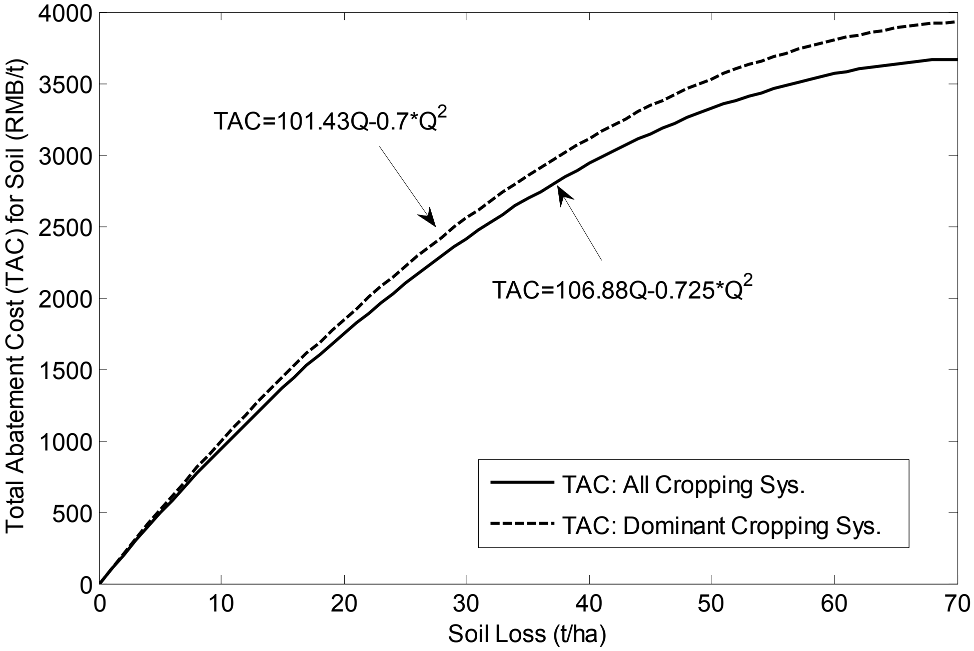

Figure 3.9. TAC Curves for Soil Loss

Note: P = Shadow Price of Soil Loss; Q = Soil Loss.

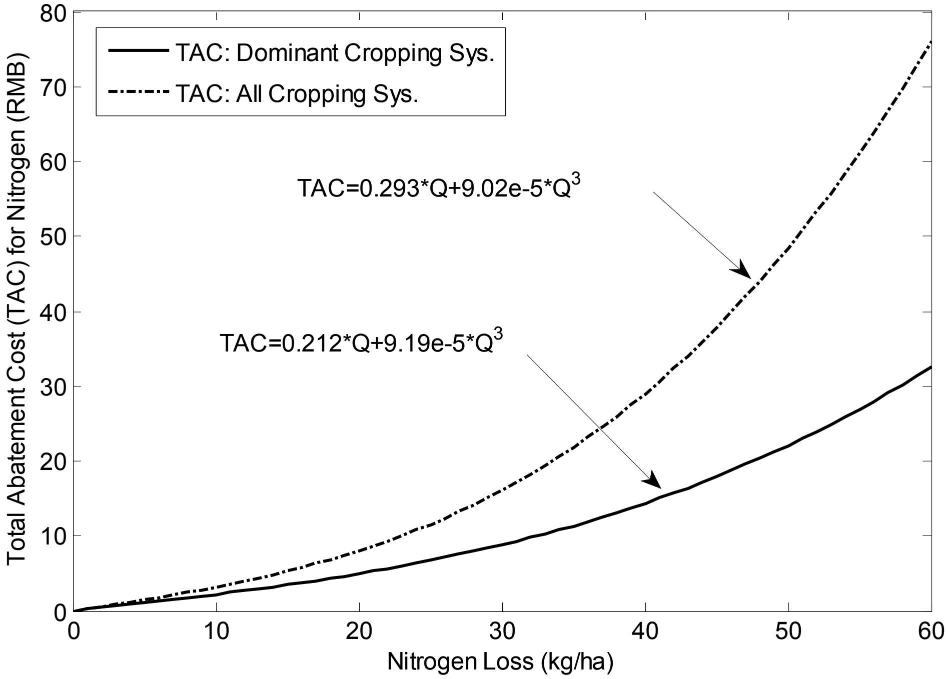

Figure 3.10. TAC Curve for Nitrogen Loss

Note: P = Shadow Price of Nitrogen Loss; Q = Nitrogen Loss.

How do my estimates of total abatement costs compare with other researchers' results? In the U.S., Pimentel et al. (1992)'s estimate of pollution costs from pesticide use account for 2.5-4% of US crop and animal revenue (approximately $200 billion). In the United Kingdom, Pretty et al.(2000) estimated water pollution costs from agriculture of £141-300 million, accounting for 1-2% of the value of gross output to UK agriculture. A more recent study by Färe et al (2006) found out that the pollution costs from the runoff and leaching of pesticides are 6% of crop and animal revenues implied by state-level data from 1960-1996. Descriptive statistics of the total abatement cost, the total revenue, and their ratio are given in Table 3.6. The mean of TAC for soil loss is 332.4 RMB/ha, and 6.9 RMB/ha for nitrogen loss. My estimate of total abatement cost accounts for 9% of the total revenue for the average cropping system.

Table3.6. Descriptive Statistics of Total Abatement Costs, Total Revenue and Their Ratio

Variables	Mean	Std. Dev.	Min	Max
TAC for Soil Loss (RMB/ha)	332.38	635.14	0.053	3928.2
TAC for Nitrogen Loss (RMB/ha)	6.92	7.18	0.004	68.50
TAC for Both (RMB/ha)	339.3	635.99	0.23	3940.5
Total Revenue(TR) (RMB/ha)	5240	1536.5	1446	12594
Ratio b/w TAC and TR	0.090	0.212	0	2.526

3.4.3 Contribution of Cropping Practice Alternatives

The results of regression analysis are shown in Table 3.7 to evaluate the marginal contribution of alternative cropping systems to the total abatement costs and the environment-adjusted farm profit. Before regression, pairwise correlations of the independent variables are tested. The regressors are only weakly correlated with each other. Heteroskedasticity-robust standard error is used to calculate t-statistics in both models. The regressors are jointly statistically significant in both models, because the overall F statistics have a p-value of 0. At the same time, 56.3% of the variation in the the total abatement cost (TAC) is explained, and 87.1% of the environment-adjusted farm profit (EFP) is explained.

Tables 3.7 to 3.10 show the *statistical* significance of the coefficients between any pair of characters of cropping systems. More important is the *economic* significance of the coefficients, meaning that measured impacts of regressors on the abatement cost and the environment-adjusted profit in Table 3.7, and the difference in abatement cost between any pair of cropping systems in Tables 3.8-3.10. Policy makers can choose appropriate economic differences when making decisions, while in this paper I report the statistical significances.

The intercept in the TAC model means that an estimation of the total abatement cost for the baseline cropping system is 119 RMB/ha. The intercept in the EFP model means that an estimation of the farm profit when facing the environmental regulations is 6316 RMB/ha. The baseline cropping system is the one with corn planted on the floodplain, using non-mulching, furrow-ridging, sufficient water and nitrogen, no terrace and low mechanization level.

In the rotation set of the TAC model, the sign of the coefficient on FWPM (i.e. flax, wheat, potato, millet) is statistically significant and positive, which implies that the abatement cost of the cropping systems with the FWPM rotation is higher than those with the mono-crop corn. The signs of the coefficients on CMP (i.e. corn, millet, potato) and MSMP (i.e. millet, soybean, millet, potato) are statistically significant and negative, which means that the CMP and MSMP rotation types generate less abatement cost compared to the mono-crop corn. The signs of the coefficients on all the with-alfalfa-rotation techniques are statistically significantly negative. This means all rotations with alfalfa generate less abatement cost.

Table 3.7. Estimation Results for the TAC and EFP Models

	Variables	**TAC**	**EFP**
Cropping Systems	Intercept	119.06*	6316.62***
Rotation[a] **(Corn)**	W	-55.99	-2322.56***
	PWC	74.20	-1588.70***
	CMP	-121.98**	-1540.22***
	CSC	5.28	-60.09
	FWPM	100.48*	-2879.68***
	PWCM	16.89	-1508.77***
	MSC	-51.80	-556.28***
	WPMCF	80.25	-2195.13***
	MSMP	-150.77**	-1909.06***
	A3CM	-394.48***	-17.15
	A3CPM	-381.06***	-613.07***
	A3MPM	-393.18***	-937.18***
	A4MPM	-410.00***	-815.87***
	FA5MC	-399.01***	-223.53***
	FWA4MC	-337.74***	-524.84***

	A3MCPCM	-354.27***	-642.34***
Residue (Non-mulching)	Mulching	-214.03***	516.25***
Practice (Furrow)	Contouring	204.31***	-181.49***
Production Situation (Irrigation + Abundant N)	Water-limit	52.00	-2374.32***
	N-limit	83.52	-2855.93***
Mechanization (Human and Animal Labor)	Mechanization	28.14	290.78***
Terracing (No Terrace)	Bench Terracing	-669.82***	1398.05***
	Spaced Terracing	-625.43***	1260.40***
Land Unit (Floodplain)	Gently Sloped	404.66***	-1358.78***
	Moderately Sloped	596.72***	-1867.98***
	Steeply Sloped	940.05***	-2565.91***
	Very Steeply Sloped	1290.31***	-3398.31***
R-square		0.563	0.871

Note: *** = significant at 1% significance level; ** = 5% significance level; * = 10% significance level; a-A# = alfalfa and years, C = corn, M = millet, F = flax, P = Potato, S = soybean, W = winter wheat; the baseline for each set of dummy variables is shown in the parentheses in Column 1.

The coefficients for conservation techniques in the TAC model are statistically significant. Compared to the non-mulching technique, the cropping systems with mulching have 214 RMB/ha less in abatement cost. Compared to furrow-ridging, the cropping systems with contouring generate 204 RMB/ha more in abatement cost. The coefficients in the terracing set in the TAC model are all statistically significantly negative. Compared to no terracing technique, the abatement cost is 670 RMB/ha less for the cropping systems with bench terracing, while 625 RMB/ha less for the spaced terracing.

The coefficients associated with three production situations and two mechanization levels in the TAC model are not significantly different from zero. This means that production situations (i.e. sufficient water and nutrient, only water-limited, only N limited) and mechanization intensification (i.e. labor force, and machine) have no significant impacts on the abatement costs.

There is no surprise that cropping systems on the floodplain generates the least abatement cost. All the positive coefficients in the land unit set are consistent with my expectation. The steeper the land, the more the abatement costs.

In the rotation set of the EFP model, the coefficients on CSC and A3CM are not statistically significant. This means that the mono-crop corn, the CSC (i.e. corn, soybean, corn) and A3CM (i.e. alfalfa 3 years, corn, millet) rotation types generate the most profit when environmental regulations imposed. The FWPM (i.e. flax, wheat, potato, millet) rotation generates the least profit when environmental regulations imposed, followed by W (i.e. wheat).

In the EFP model, the conservation technique mulching generates 516 RMB/ha more in profit compared to non-mulching, when environmental regulations imposed. Contouring has 181 RMB/ha less in environment-adjusted profit, compared to furrow-ridging. Both bench terracing and spaced terracing contribute over 1000 RMB/ha in farm profit, compared to no terracing. There is no surprise the cropping systems in the floodplain generates the most profit when environmental policy implemented.

The results in Table 3.7 can only imply the difference from the baseline technique in the abatement costs. For the conservation techniques with two or more dummy variables, farmers and policy makers might be interested in comparing any pair of the techniques. For example, among all the 17 rotation types, the comparison in abatement cost between CSC (corn, soybean, corn) and A3CM (alfalfa 3 years, corn, millet) may be important, which is not provided directly by the estimation results. The abatement cost matrices calculated from the estimation results can be utilized to show the difference in the abatement cost between any pair of cropping systems. The same process can be applied to the EFP model to figure out the difference in the profit when environmental regulations imposed.

The abatement cost matrix for crop rotation types (Table 3.8) implies that the FWPM (i.e. flax, wheat, potato, millet) rotation contributes the most to the abatement cost, followed by the mono-crop corn. The rotation types with alfalfa contribute the least to the abatement cost, and there is not much difference between them in abatement cost. Among the non-alfalfa rotation types, the CMP (i.e. corn, millet, potato) and MSMP (i.e. millet, soybean, millet, potato) rotation have the least abatement cost.

The abatement cost matrix for terracing techniques (Table 3.9) implies that the abatement cost for the cropping systems with bench terracing and spaced terracing will be about 600 RMB/ha less, compared to no terrace. There is no significant difference in abatement cost between bench terracing and spaced terracing.

The abatement cost matrix for types of land units (Table 3.10) implies the slope of the land play an important role in the abatement cost. The steeper the land, the more the abatement cost. For example, compared to the systems on the floodplain, those on most steeply sloped land will cost 1290 RMB/ha more in abating pollution.

Table 3.8. Abatement Cost Matrix for 17 Cropping Rotation^{a}

Reference:	C	W	PWC	CMP	CSC	FWPM	PWCM	MSC	WPMCF	MSMP	A3CM	A3CPM	A3MPM	A4MPM	FA5MC	FWA4MC	A3MCPCM
C	0																
W	-55.99	0															
PWC	74.20	130.19**	0														
CMP	-121.98**	-65.99	-196.18***	0													
CSC	5.28	61.27	-68.92	127.26**	0												
FWPM	100.48*	156.47***	26.28	222.46***	95.20	0											
PWCM	16.89	72.88	-57.31	138.87**	11.61	-83.59	0										
MSC	-51.80	4.19	-126.00**	70.18	-57.08	-152.28***	-68.69	0									
WPMCF	80.25	136.24 **	6.05	202.23***	74.97	-20.23	63.36	132.05**	0								
MSMP	-150.77**	-94.78*	-224.97***	-28.79	-156.05***	-251.25***	-167.66***	-98.97*	-231.02***	0							
A3CM	-394.48***	-338.49***	-468.68***	-272.50***	-399.76***	-494.96***	-411.37***	-342.68***	-474.73***	-243.71***	0						
A3CPM	-381.06***	-325.07***	-455.26***	-259.08***	-386.34***	-481.54***	-397.95***	-329.26***	-461.31***	-230.29***	13.42	0					
A3MPM	-393.18***	-337.19***	-467.38**	-271.20***	-398.46***	-493.66***	-410.07***	-341.38***	-473.43***	-242.41***	1.30	-12.13	0				
A4MPM	-410.00***	-354.01***	-484.20***	-288.02***	-415.28***	-510.48***	-426.89***	-358.20***	-490.25***	-259.23***	-15.52	-16.81	-4.68	0			
FA5MC	-399.01***	-343.02***	-473.21***	-277.03***	-404.29***	-499.49***	-415.90***	-347.21***	-479.26***	-248.24***	-4.53	10.98	23.11	27.79	0		
FWA4MC	-337.74***	-281.75***	-411.94***	-215.76***	-343.02***	-438.22***	-354.63***	-285.94***	-417.99***	-186.97***	56.74	61.27	73.40	78.08	50.29	0	
A3MCPCM	-354.27***	-298.28***	-428.47***	-232.29***	-359.55***	-454.75***	-371.16***	-302.47***	-434.52***	-203.50***	40.21	-16.52	-4.39	0.29	-27.50	-77.79	0

Note: 0 = no significant difference; * significantly different at 10% level; ** significantly different at 5% level;*** = significantly different at 1% level.

a-A# = alfalfa and years, C = corn, M = millet, F = flax, P = potato, S = soybean, W = winter wheat.

Table 3.9. Abatement Cost Matrix for 3 Terracing Techniques

Reference:	**No Terracing**	**Bench Terrace**	**Spaced Terrace**
No Terracing	0		
Bench Terrace	-669.82***	0	
Spaced Terrace	-625.43***	44.39	0

Note: 0 = no significant difference; * = significantly different at 10% level;** = significantly different at 5% level;*** = significantly different at 1% level.

Table 3.10. Abatement Cost Matrix for 5 Types of Land Units

Reference:	**Floodplain**	**Gently**	**Moderately**	**Steeply**	**Very Steeply**
Floodplain	0				
Gently^{a}	404.66***	0			
Moderately	596.72***	192.06 ***	0		
Steeply	940.05***	535.39 ***	343.33 ***	0	
Vey Steeply	1290.31 ***	885.65 ***	693.59 ***	350.26 ***	0

Note: *** denotes significant at 1% significance level; ** 5% significance level; *10% significance level.

a-Gently = gently sloped land; Moderately = moderately sloped land; Steeply = steeply sloped land; Very Steeply = very steeply sloped land.

3.5 Conclusion and Discussion

Sustainable development in the Loess Plateau of China is threatened by its fragile ecosystem and huge population. A lot of land with a slope more than 25% had been planted to trees through the Grain for Green program. This program contributed a lot in reducing soil and water loss. However, young male farmers, who had been living on their land, have to migrate to and work in urban areas to support their family, leaving their elderly parents and children at home. This is harmful to the sustainable development at the rural family level. I wonder whether some cropping systems, instead of the extreme conservation techniques like planting trees, can balance both the economic and environmental goals. The cropping systems with higher economic profit when facing some environmental regulations are recommended to farmers and policy makers.

Following previous research, this chapter estimated the shadow prices for two agricultural pollutants, i.e. nitrogen loss and soil loss, in the crop sector of the Loess Plateau of China. Further, in this chapter I proposed EAP as a more appropriate index to estimate the costs from environmental regulations. Finally, I analyzed the contribution of alternative cropping systems to the abatement costs and the environment-adjusted farm profit. The conclusions are as follows:

(1) Marginal abatement cost of nitrogen loss averaged at 0.383 RMB/kg, and ranges from 0.21 to 1.29 RMB/kg. Soil loss has a mean marginal abatement cost of 0.102 RMB/kg, ranging from 0-0.162 RMB/kg.

(2) The MAC curve for soil loss is downward sloped, while the MAC curve for nitrogen loss is upward sloped.

(3) The rotation types with alfalfa generate the least abatement cost, compared to those without alfalfa. Among the non-alfalfa rotation systems, the CMP (i.e. corn, millet, potato) and MSMP (i.e. millet, soybean, millet, potato) rotation have the least abatement cost.

(4) The conservation techniques mulching, furrow-ridging and terracing contribute less to the abatement cost, compared to non-mulching, contouring and no terracing, respectively.

(5) The mono-crop corn, the CSC (i.e. corn, soybean, corn) and A3CM (i.e. alfalfa 3 years, corn, millet) rotation types are recommended to farmers, because they generate the most profit if environmental regulations were imposed. The reason for promoting growing corn as mono-crop and in rotations might be its potential high yield. This is consistent with the conclusion from Lu et al (2003).

(6) The conservation techniques mulching, furrow-ridging and terracing are more profitable to farmers, compared to non-mulching, contouring and no terracing, respectively.

(7) The cropping systems on the most steeply sloped land will lose about 3400 RMB/ha in farm profit, compared to those on the floodplain, if environmental regulations were imposed.

(8) EAP is a more appropriate measurement for costs from environmental regulations than abatement costs from a shadow pricing model.

CHATPTER 4

SUSTAINABLE VALUE AND EFFICIENCY OF CROPPING SYSTEMS IN THE LOESS PLATEAU OF CHINA

4.1 Introduction

Sustainable development is a normative concept that can guide development strategies to balance environmental and socio-economic issues across different sectors, locally to globally. More specifically, sustainable agriculture prescribes "practices that meet current and future societal needs for food and fiber, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered." (Tilman *et al.*, 2002, pp.671). Agricultural sustainability centers on productive and accessible agricultural practices that have few adverse effects on environmental goods and services (Pretty, 2008). For example, no-till agriculture produces erosion rates much closer to soil production rates than conventional agriculture (Montgomery, 2007), and therefore helps contribute toward sustainability.

Goods and services from agricultural systems depend on a stock of assets, including natural, human and financial capital. Cropping systems can erode natural capital, like soils, depending on practices and technologies used, such as crop rotations and tillage. Sustainability therefore depends largely on how cropping systems are managed and how they interact with the capital endowments where they are produced. It is essential of course to consider these systems through economic, social and environmental perspectives.

Sustainable development in the agriculture of the Loess Plateau is a big concern for both scientists and policy makers (Lu, 2000) because of its fragile ecosystem and huge population. Much of the agricultural land has already been planted to trees through the Grain for Green program (Feng *et al.*, 2005) due to its high vulnerability. Planting land to permanent forests is an extreme conservative measure. Ecological trees generate little economic return to farmers, who make a living mostly on their land. Many young male labors have to migrate to urban areas in order to compensate for lost farm jobs, leading to many social issues connected to the community. One example is child-care when only the elderly and children left behind (Li *et al.,* 2012).

There is no doubt that policy makers aim to realize both strong economic performance and sustainable use of natural resources in agriculture (Liu, 1999; Wang *et al.*, 2003; Fan *et al.*, 2005). Balancing economic and environmental goals will require an integrated assessment of agricultural sustainability to provide guidance if decision makers are to consider crops rather than converting to trees. Therefore, it is important to measure and assess agricultural sustainability using appropriate indicators. The purpose of this paper is to evaluate sustainability for different cropping systems in the Loess Plateau of China, and identify sustainable cropping systems that balance economic and environmental goals.

Although the concept of sustainability is important, its measurement is not without considerable difficulties. Environmental efficiency (See Tyteca (1996) for a review) is an indicator to estimate sustainability from the environmental perspective, which is generally obtained by making adjustments to standard parametric and non-parametric efficiency analysis techniques (Coelli *et al.*, 2007). For example, Reinhard et al. (2000) estimated the environmental efficiency for Dutch dairy farms by stochastic frontier analysis and data envelope analysis (DEA). In their study, environmental efficiency was defined as the ratio of the minimum feasible to observed-use of environmentally detrimental inputs, conditional on the observed levels of outputs and conventional inputs.

Eco-efficiency is another popular indicator related to the notion of sustainability, which concerns the capacity to produce goods and services while causing minimal environmental degradation. Defined as the ratio of economic value added over environmental damage, its score can be measured with the DEA method (Kuosmanen and Kortelainen, 2005). An eco-efficiency analysis of industrial systems in China was conducted by Zhang et al. (2008) using DEA approach with data from 30 provinces. Their results indicate that Tianjin, Shanghai, Guangdong, Beijing, Hainan and Qinghai are relatively eco-efficient. Although eco-efficiency is a sound conceptual and practical instrument for sustainability analysis, Figge and Hahn (2004) point out three major shortcomings. First, as a relative measure, eco-efficiency does not provide any information about eco-effectiveness. Second, an improved eco-efficiency does not guarantee effectiveness in using environmental resources. Third, eco-efficiency is not inclusive of all social and environmental aspects.

To overcome the shortcomings of eco-efficiency, Figge and Hahn (2004, 2005) proposed a sustainable value approach to measure corporate contributions to sustainability, which considers economic, environmental and social aspects simultaneously. Van Passel et al. (2007) applied this technique to measure farm sustainability and explained differences in sustainable efficiency of Flemish dairy farms. They later updated this approach by combining it with frontier efficiency benchmarks (Van Passel et al., 2009).

This chapter will estimate the sustainable value and efficiency of different cropping systems in the Loess Plateau of China by the sustainable value approach. Policy makers can use sustainable value and efficiency to measure, monitor and communicate sustainability performance over space and time. More specifically, cropping systems with higher sustainable value and efficiency can be recommended to policy makers in the Loess Plateau to achieve the balance between economic and environmental goals. Different from the parametric estimation of the frontier benchmarks proposed by Van Passel et al. (2009), I propose to calculate best-performance benchmarks by a DEA method. I also add a regression model to measure the contributions of alternative conservation practices to sustainability. Further, some matrices are provided to compare the sustainable value and efficiency between any two cropping systems.

In Section 4.2, I present the methodologies, including the sustainable value approach and a regression model. In Section 4.3, I discuss the simulation data for the Loess Plateau created from the Environmental Policy Integrated Climate (EPIC) model. The dataset has at least two strengths. One is the availability of natural capital data such as soil and nitrogen. The other is that over 1720 possible cropping systems are included. In Section 4.4, I report the empirical results, including the sustainable value and efficiency matrices for alternative cropping systems. Section 4.5 concludes and discusses this study.

4.2 Methodology

4.2.1 The Sustainable Value Approach

Strong sustainability and weak sustainability are two relevant paradigms of sustainable development. According to strong sustainability, a firm contributes the most to sustainable development if it uses every single form of capital more efficiently than other firms. However, in practice there is no such super-efficient firm. Weak sustainability requires only that a more sustainable firm has higher efficiency in the use of one form of capital that can compensate for the lower efficiency of the use in another form of capital (Figge and Hahn, 2005). It allows the substitution between all forms of capital to some degree (Cabeza Gutés, 1996). As soil degradation becomes more severe, soil is recognized as scarce natural capital, which can be combined and substituted with other forms of capital in cropping sectors.

Figge and Hahn (2004, 2005) developed a value creation approach by applying the logic of capital cost, value spread and economic value in financial markets to a whole set of different forms of capital and a broader definition of value created. They call it the sustainable value approach. Capital cost, measured as opportunity cost, is the value created by a unit of capital in the market, and implies the value that would have been created by an alternative use of that capital. Value spread represents how much more value is created by a unit of capital in a firm than in the market if the firm uses capital more efficiently than the market. The excess value created by the firm is calculated by multiplying the value spread by the amount of capital employed by the firm. That is, a firm creates a positive economic value if the value created by the firm is higher than the value that would have been obtained by investing the same amount of capital in the market.

Analogically, key terms in sustainable development are defined by following Figge and Hahn (2004, 2005). In the sustainable value approach, capital refers to all types, including financial capital, human capital and natural capital. Opportunity cost, also called capital cost, is the value added per unit of capital by the benchmark. Opportunity cost measures the value that can be created by alternative use of the capital. If one universal benchmark is chosen for all cropping systems, then the fixed opportunity cost can be calculated as:

$$\text{opportunity cost} = \frac{\text{value added}_{\text{benchmark}}}{\text{capital}_{\text{benchmark}}}.$$

Equation 4.1

If a unique benchmark is assigned to each observation, then the opportunity cost varies and therefore for the ith cropping system, its opportunity cost can be computed by:

$$\text{opportunity cost}_i = \frac{\text{value added}_{i,\text{benchmark}}}{\text{capital}_{i,\text{benchmark}}}.$$

Equation 4.2

The market is chosen as the universal benchmark in the financial area. I will discuss the choice of individual benchmark(s) in the sustainability domain in Section 4.2.3.

The value spread for the ith cropping system reflects how much more value is created using some form of capital, compared to the benchmark. It can be calculated by:

$$\text{value spread}_i = \frac{\text{value added}_i}{\text{capital}_i} - \text{opportunity cost}_i.$$

Equation 4.3

Corresponding to the economic value in the financial area, the sustainable value created by firm i can be calculated by adding up the value contributions from every form of capital $s = 1, \ldots, n$ (Van Passel *et al.*, 2007). Sustainable value is a monetary measure of sustainability. Monetary measures have an advantage of informing policy makers on sustainability in terms (i.e. dollars) that they are familiar with. They can also compare the monetary measure of sustainability in dollars with other economic values. Mathematically,

$$\text{sustainable value}_i = \frac{1}{n}\sum_{s=1}^{n}(\text{value spread}_i^s \cdot \text{capital}_i^s).$$

Equation 4.4

Note that dividing by n does not serve to weight different forms of capital but only to avoid multi-counting of value creation (Figge and Hahn, 2005).

Sustainable efficiency for the ith cropping system is the ratio between the value added and the cost of sustainability capital for the firm (Figge and Hahn, 2005). Its mathematical form is:

$$\text{sustainable efficiency}_i = \frac{\text{value added}_i}{\text{cost of sustainability capital}_i}.$$

Equation 4.5

The more efficient a firm is from a sustainable standpoint, the more its value added exceeds its cost of sustainable capital. The cost of sustainability capital for the ith cropping system is given by the difference between the value added and the sustainability value for this system, i.e.

$$\text{cost of sustainability capital}_i = \text{value added}_i - \text{sustainable value}_i.$$

Equation 4.6

Given the value added, the more sustainable value a firm creates, the less will be its cost of sustainability capital. By combining Equation 4.5 and Equation 4.6, the sustainability efficiency for the ith cropping system can be calculated as:

$$\text{sustainable efficiency}_i = \frac{\text{value added}_i}{\text{value added}_i - \text{sustainable value}_i}.$$

Equation 4.7

The sustainable efficiency score is one if the value added by a firm covers the cost of all forms of capital (i.e. cost of sustainability capital). A sustainable efficiency higher than one means that the firm is overall more efficient than the benchmark.

A simple example is given in Table 4.1 to show how to apply the sustainable value approach to calculate sustainable value and efficiency. Assuming Firm 0 is chosen as the universal benchmark, the value added and three types of capital of Firm 0 are used to calculate the opportunity cost for all firms. For example, the opportunity cost of human capital is 100, computed by dividing the value added from Firm 0 (i.e. 1000) by the human capital from Firm 0 (i.e. 10). The value spread of human capital from Firm 1 is –50, calculated by 600/12 – 100. The sustainable value of Firm 1 is –200, computed by $\left(\frac{1}{3}\right) \times [(-50) \cdot 12 + (-1) \cdot 150 + (-0.1) \cdot 1500]$. The cost of sustainable capital is the difference between the value added and the sustainable value, i.e. $600 - (-200) = 800$. The sustainable efficiency for Firm 1 is 0.75, calculated by dividing the value added (i.e. 600) by the cost of sustainable capital (i.e. 800). Compared to Firm 0, Firm 1 loses 200 dollars in sustainable value. Its efficiency from a sustainability standpoint can be improved at least by 0.25 to the level of Firm 0.

Table 4.1. A Simple Example of Calculating Sustainable Value and Efficiency

Basic Data	**Firm 0 (Benchmark)**	**Firm 1**
Value Added ($)	1000	600
Human Capital (Labor)	10	12
Natural Capital (Energy Use)	200	150
Economic Capital ($)	2000	1500
Opportunity Cost		
Human Capital	100 = 1000/10	100 = 1000/10
Natural Capital	5 = 1000/200	5 = 1000/200
Financial Capital	0.5 = 1000/2000	0.5 = 1000/2000
Value Spread		
Human Capital	0 = 1000/10 – 100	–50 = 600/12 – 100
Natural Capital	0 = 1000/200 – 5	–1 = 600/150 – 5
Financial Capital	0 = 1000/2000 – 0.5	– 0.1 = 600/1500 – 0.5
Sustainable Value($)	0	–200[a]
Cost of Sustainable Capital	1000 = 1000 – 0	800 = 600 – (– 200)
Sustainable Efficiency	1	0.75 = 600/800

a. $-200 = (1/3) \times [(-50) \times 6 + (-1) \times 150 + (-0.1) \times 1500]$.

4.2.2 Steps to Calculate Sustainable Value and Efficiency

Three steps can be used to calculate sustainable value and efficiency, as explained by Van Passel et al. (2009). Firstly, the scope of the analysis needs to be determined. That is, what activities and what entities will be analyzed. In this paper, 2006 distinct cropping systems are chosen as entities (also called firms), which employ all forms of capital to create value. Different cropping systems are characterized by various technologies and practices such as crop rotations and terracing.

Secondly, the relevant resources need to be identified. Considering sustainable development, the importance of the capital forms used by a firm can be judged by the scarcity or degree of depletion of the capital (Figge and Hahn, 2005). The Loess Plateau in China, as one of the most severely degraded areas in the world, has over 60% of its land subjected to soil degradation, with an average annual soil loss of 2000-2500 t/km^2 (Shi and Shao, 2000). Associated with soil loss is nitrogen loss. Thus, soil loss and nitrogen surplus are recognized as two natural capital forms in this study. Soil and nitrogen data are rare to observe at the farm level or national level. Fortunately, a simulation model, verified by experiments, can provide accurate estimates of soil and nitrogen losses associated with various cropping practices. In addition to natural capital, financial capital and human capital are also taken into account through enterprise budgeting.

Thirdly, the appropriate benchmarks need to be determined. Four possible benchmarks were proposed by Van Passel *et al.* (2007). First, the weighted average of a sample can be used. For example, cropping systems with conservation practices can be chosen as a sample to calculate benchmarks. Second, a super-efficient firm, that uses every single type of capital in the most efficient way, can serve as the super-efficient benchmark. In practice, a super-efficient cropping system is highly unlikely. Third, a performance target is can be used as a benchmark. An example given by Van Passel et al. (2007) is 150 kg N ha^{-1} for the farm gate N surplus for dairy farms. Fourth, the unweighted average of all firms in the sample can also be used as a benchmark.

Figge and Hahn (2005) used the British economy in year 2001 as benchmark to evaluate the sustainability performance of British petroleum companies. Van Passel et al. (2007) opted for the weighted average as a benchmark to measure dairy farm sustainability. Later, they updated the benchmark choice to frontier efficiency benchmarks (Van Passel *et al.*, 2009). The Cobb-Douglas and translog functional forms were used to construct best performance benchmarks. They also pointed out that the most important advantage of using frontier efficiency benchmark is that the sustainable value approach takes the link between the output produced and the resources used into account. I update their frontier efficiency benchmark by a DEA method in next section.

4.2.3 DEA Method to Formulate the Benchmark

The benchmark choice reflects a normative judgment of sustainable development, and determines the way to explain the sustainable value (Van Passel *et al.*, 2009). It should therefore be chosen with great care. Since I want to identify the most sustainable cropping systems, the best performance benchmark is preferred. A performance target may also be appropriate, but it may not be easy to specify the reasonable target level. In this paper, many possible cropping systems for the Loess Plateau are considered. The frontier constructed by the possible cropping systems may serve as a reasonable target.

Instead of the parametric frontier benchmark proposed by Figge and Hahn (2005), I adopt a non-parametric data envelope analysis (DEA) to determine benchmarks. Both parametric and non-parametric approaches have been proposed in the frontier literature. Data noise can be taken into account in the parametric approach, but the specification error may arise with the choice of the functional form. Since my data is simulated by the EPIC model (refer to Section 3), data noise is not expected to play an important role in the estimation of production frontier. The DEA approach is chosen to avoid functional form specification error. The DEA method is also easier to calculate, especially when multiple capital types are considered in the production process. Another advantage is that a unique frontier benchmark is specified for each cropping system through considering the technology possibility.

Denote all inputs by $x \in \Re_{+}^{N}$, all desirable outputs by $y \in \Re_{+}^{M}$ and all undesirable outputs by $w \in \Re_{+}^{J}$. The technology set S can be defined as:

$$S = \{(y, w): x \text{ can produce } y \text{ and } w\}.$$

The key tool used to formulate the best performing benchmark is the input distance function, denoted by $D_i(y, w, x)$. It can be defined as (Färe *et al.*, 1996):

$$D_i(y, w, x) = \max\left\{\rho: \left(\frac{x}{\rho}, y, w\right) \epsilon S\right\}.$$

This function measures the extent that inputs can be decreased to reach the efficient frontier. $D_i = 1$implies the observation is on the frontier, and no reductions in inputs is possible, while $D_i > 1$ means that the observation will be efficient if the inputs x are reduced to x/D_i. As Färe et al. (1996) pointed out, since the same factor λ is applied to all inputs, only equiproportional reduction of inputs is considered.

Suppose we have $i = 1, \dots, I$ observations on N inputs, M desirable outputs and J undesirable outputs. Based on the dataset, the technology set can be constructed as follows (see Färe et.al, 1996):

$$S = \{(x, y, w): \sum_{i=1}^{I} \lambda^i x_n^i \le x_n, n = 1, \dots, N$$

$$\sum_{i=1}^{I} \lambda^i y_m^i \ge y_m, m = 1, \dots, M$$

$$\sum_{i=1}^{I} \lambda^i w_j^i = w_j, j = 1, \dots, J$$

$$\lambda^i \ge 0, i = 1, \dots, I\}$$

The input distance function for each observation can be computed by solving the following linear programming problem:

$$(D_i(y^i, w^i, x^i))^{-1} = \min_{\rho, z} \rho$$

$$\text{s.t. } \textstyle\sum_{i=1}^{I} \lambda^i x_n^i \le \rho x_n, n = 1, \dots, N$$

$$\sum_{i=1}^{I} \lambda^i y_m^i \ge y_m, m = 1, \dots, M$$

$$\sum_{i=1}^{I} \lambda^i w_j^i = w_j, j = 1, \dots, J$$

$$\lambda^i \ge 0, i = 1, \dots, I$$

Therefore, the opportunity cost of the ith firm with a DEA benchmark can be updated by:

$$\text{opportunity cost}_i = \frac{\text{value added}_{\text{benchmark}}}{\text{capital}_{\text{benchmark}}} = \frac{\text{value added}_i}{\frac{\text{capital}_i}{D_i}}.$$

Equation 4.8

Sustainable value and sustainable efficiency can also be updated based on the DEA benchmark, as explained above.

4.2.3 Contribution of Conservation Practice Alternatives

To analyze what factors influence the sustainability of cropping system, an econometric model can be formulated as follows:

$$Y_i = \beta_0 + \boldsymbol{\beta_1 ROT_i} + \boldsymbol{\beta_2 RES_i} + \boldsymbol{\beta_3 CONT_i} + \boldsymbol{\beta_4 PRO_i} + \boldsymbol{\beta_5 MEC_i} + \boldsymbol{\beta_6 TER_i} + \boldsymbol{\beta_7 SLP_i} + \varepsilon_i,$$

Equation 4.9

where the dependent variable Y_i is the sustainable value or efficiency of the i^{th} cropping system, calculated from the sustainable value approach. Cropping systems are characterized by different cropping practices, which are represented by sets of dummy variables: $\mathbf{ROT_i}$ is a set of dummy variables for crop rotations, $\mathbf{RES_i}$ for crop residue management, $\mathbf{CONT_i}$ for contour or furrow ridging, $\mathbf{PRO_i}$ for production situations, $\mathbf{MEC_i}$ for mechanization level, $\mathbf{TER_i}$ for terraces, and $\mathbf{SLP_i}$ for land steepness. All βs are parameters to be estimated. ε_i is the error term.

The estimated parameters capture the marginal contribution of alternative conservation techniques. For example, the dummy variable RES_i takes the value of 1 if mulching is adopted; otherwise, it equals zero. The coefficient β_2 is expected to be positive, and in the sustainable value model means that crop mulching contributes β_2 dollars to sustainable value compared to a non-mulching technique. Some conservation techniques have more than two options. For example, crop rotation techniques include 17 alternatives in this study, and therefore 16 dummy variables are used for rotation in the regression model. The coefficients corresponding to the 16 dummy variables are the marginal contribution of each cropping rotation, compared to the basis rotation. However, policy makers may be interested in the comparison in sustainable value and efficiency between any pair of the 17 rotations. Therefore, sustainable value and sustainable efficiency matrices are constructed, based on the regression results with marginal sustainable values and efficiency scores between any pair of cropping systems being the entries of the matrices.

4.3 Data

This study employs the simulation data from Environmental Policy Integrated Climate (EPIC) model, applied and validated with the experimental data in Ansai County of Loess Plateau by Lu (2000). EPIC is a comprehensive simulation model designed to predict the effects of management decisions on soil, water, nutrient and pesticide movements and their combined impact on soil loss, water quality and crop yield (Williams *et al.*, 2006). It consists of weather, surface runoff, water and wind erosion, nitrogen leaching, pesticide fate and transport, crop growth and yield, crop rotations, tillage, plant environment control (drainage, irrigation, fertilization, furrow diking, liming), economic accounting, waste management, etc. A comprehensive dataset regarding soil, weather, crop management and parameters, and fertilizer can meet the basic requirement to run the model. Thousands of equations are used to simulate many processes such as crop growth and soil erosion. For more information on the model, refer to Williams et al.(1983), Gassman et al.(2005) and Williams et al.(2006).

To apply the sustainable value approach with DEA benchmarks, the value added and capital need to be specified. Revenue derived from crop yield is specified as "value added" in the sustainable value approach. To cope with the multidimensionality, I assume each cropping system uses all forms of capital to produce crop revenue. Natural capital is more difficult to measure than economic and social capital in practice. The EPIC model provides an opportunity to measure soil loss and nitrogen surplus accurately. I treat soil loss and nitrogen surplus from the EPIC model as natural capital inputs in the production process. Financial capital is calculated by aggregating all the costs of conventional inputs, including seeds, nutrients (N, P and K), biocides, irrigation if applicable, farm equipment (including seeding machines, knapsack sprayers, plough, hoes, cutters and threshers). The social capital includes labor costs.

The advantage of a simulation model is that many potential scenarios can be evaluated easily and quickly. 2006 cropping systems were specified by Lu (2000). The dataset used in this study includes 5 land units, 17 crop rotations, 3 production situations, 3 terracing techniques, 2 tillage techniques, 2 crop residue management techniques and 2 mechanization levels (Table 4.2). As shown in the methodology section, the benchmark is critical to the measurement of sustainable value and efficiency. A comprehensive dataset such as this helps determine the absolute best-performance benchmarks.

Table 4.2. Cropping Systems Identified and Measured by Lu (2000)

Categories	Specifications
Land units	**5** units classified by land slope steepness: floodplains, gently steeply sloped land, moderately steeply sloped land, steeply sloped land, and very steeply sloped land
Crop rotation types[a]	**2** mono crops: C and W **8** types of rotation without alfalfa: PsWC, CMPa, CSC, FWPaM, PsWCM, MSC, WPaMCF, MSMPa **7** types of rotation with alfalfa: A3CM, A3CPaM, A3MPaM, A4MPaM, FA5MC, FWA4MC, A3MCPaCM
Production situations	**3** situations with different availability of water and nutrients: sufficient water and nitrogen, water-limited and nitrogen-limited
Conservation Techniques	**4** techniques: contouring + mulching, contouring + non-mulching, furrow-ridging + mulching, furrow-ridging + non-mulching.
Mechanization levels	**2** levels: human and animal labor, semi-mechanization

a-A#=alfalfa and years, C=corn, M=millet, F=flax, Ps=Summer Potato, Pa=Autumn Potato, S=soybean, W=winter wheat

Descriptive statistics of the data used in this paper are given in Table 4.3. Revenue and cost except labor cost in monetary units are used to calculate "value added" in the sustainable value approach. The natural capital soil and nitrogen are in physical units, while financial capital and social capital are in monetary units. On average, 5221 RMB in revenue can be produced by 3112 kg soil loss and 15.3 kg nitrogen surplus as natural capital, 1654 RMB cost except labor and 1390 RMB labor. Input and output prices used to calculate revenue and cost are shown in Table 4.4.

Table 4.3. Descriptive Statistics of Value Added and Capital for 2006 Cropping Systems

Variable	Terms in SV[a] approach	Mean	Standard Deviation	Minimum	Maximum
Revenue (RMB/ha)	Used to calculate Value Added	5221	1483	1446	12594
Cost except labor (RMB/ha)	Used to calculate Value Added	1654	776	506	4561
Soil Loss(kg/ha)	Natural capital	3112	7480	0	69838
Nitrogen Surplus (kg/ha)	Natural capital	15.3	9.4	0.01	57.6
Labor(RMB/ha)	Social capital	1390	682	87	2942

a-SV= the sustainable value approach; 1 US dollar = 6.3 RMB at year 2012.

Table 4.4. Input and Output Prices Used to Calculate Revenue, Financial and Human Capital[a]

Input Name	Input Price	Unit	Output Name	Output Price	Unit
Nitrogen (N)	2.9	RMB/kg	Corn	1.24	RMB/kg
Phosphorus (P)	7.8	RMB/kg	Millet	1.28	RMB/kg
Potassium(K)	4.8	RMB/kg	Wheat	1.40	RMB/kg
Biocide	40.0	RMB/kg	Soybean	2.40	RMB/kg
Human Labor	10.0	RMB/day	Autumn Potato	0.60	RMB/kg
Oxen Labor	20.0	RMB/day	Summer Potato	0.90	RMB/kg
Donkey Labor	15.0	RMB/day	Flax	1.68	RMB/kg
-	-	-	Alfalfa	0.60	RMB/kg

Source: Lu (2000)

a-1 US dollar = 6.3 RMB at year 2012

4.4 Empirical Results

4.4.1 DEA Benchmarks

The four benchmarks proposed by Van Passel *et al.*(2007) are fixed to all firms. However, the DEA approach can assign a unique benchmark to each obervation, through considering the possibility technology. The inputs of the benchmark corresponding to the ith cropping system are calculated by dividing the observed inputs from the ith cropping system by its input distance function. The outputs are kept the same. The technology set in this paper is defined as 2006 distinct cropping systems that produce revenue from natural capital, financial capital, and human capital. The mean of the input distance functions for all 2006 cropping systems is 1.742 (Table 4.5), which implies on average the same amount of output can be produced by using only 57.4% (i.e. 1/1.742) of the observed inputs. Descriptive statistics of the inputs from the 2006 benchmark cropping systems are also given in Table 4.5. For example, the mean of soil loss for all 2006 benchmark systems is 1398 kg/ha, and it has a large range from 0 to 31,272 kg/ha.

Table 4.5. Descriptive Statistics of Input Distance Functions and the Benchmark Inputs

Variable	Mean	Standard Deviation	Minimum	Maximum
Input Distance function	1.742	0.540	1	4.733
Soil Loss(kg/ha)	1398	3084	0	31272
Nitrogen Surplus(kg/ha)	8.8	5.9	0.014	54
Labor (RMB/ha)	839	447	40	2034

4.4.2 Sustainable Value and Sustainable Efficiency

Descriptive statistics of sustainable value and sustainable efficiency for all 2006 cropping systems are shown in Table 4.6. The sustainable value is non-positive for all cropping systems. Since the best performing cropping systems are chosen as benchmarks, a sustainable value of 0 would indicate that the cropping system uses all its resources in the most productive way. The cropping systems with zero in sustainable value are the most sustainable. Large differences in sustainable value of all 2006 cropping systems are observed, ranging from -4700 to 0 RMB/ha. The sustainable value of cropping systems can be improved by applying their resources in a more productive way, in other words, by moving towards the production frontier. The mean of sustainable value is -1661 RMB/ha, which means compared to the most sustainable cropping systems, the average cropping system loses 1661 RMB/ha in sustainable value.

The sustainable efficiency under DEA benchmarks is between 0 and 1. A sustainable efficiency of 1 indicates that the cropping systems are the most efficient from a sustainability perspective, while 0 implies the least efficiency. The mean of the sustainable efficiency for all cropping systems is 0.689, which means on average the sustainable efficiency can be improved by 31.1% at most.

The histograms shown in Figure 4.1 and Figure 4.2 indicate the distribution information of the sustainable values and sustainable efficiency scores. The distribution of the sustainable values is screwed with a large left tail, while the sustainable efficiency has a small left tail.

Table 4.6. Descriptive Statistics of Sustainable Value and Efficiency for 2006 Cropping Systems

	Mean	Standard Deviation	Minimum	Maximum
Sustainable Value (RMB/ha)	-1661	1013	-4700	0
Sustainable Efficiency	0.689	0.165	0.263	1

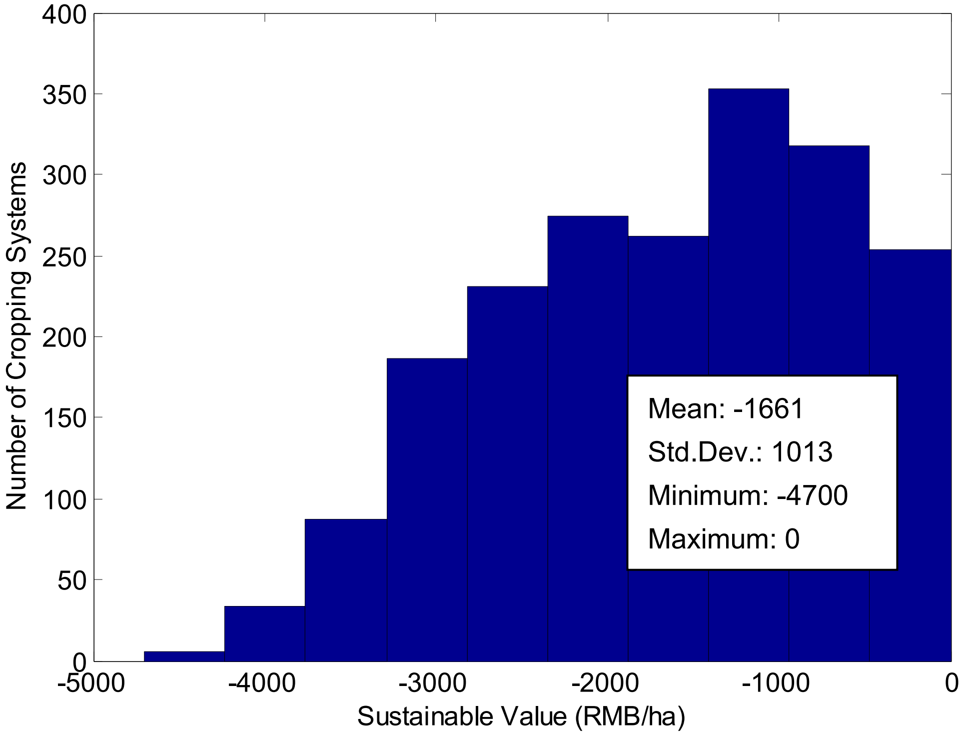

Figure 4.1. Histogram of Sustainable Value for All Cropping Systems

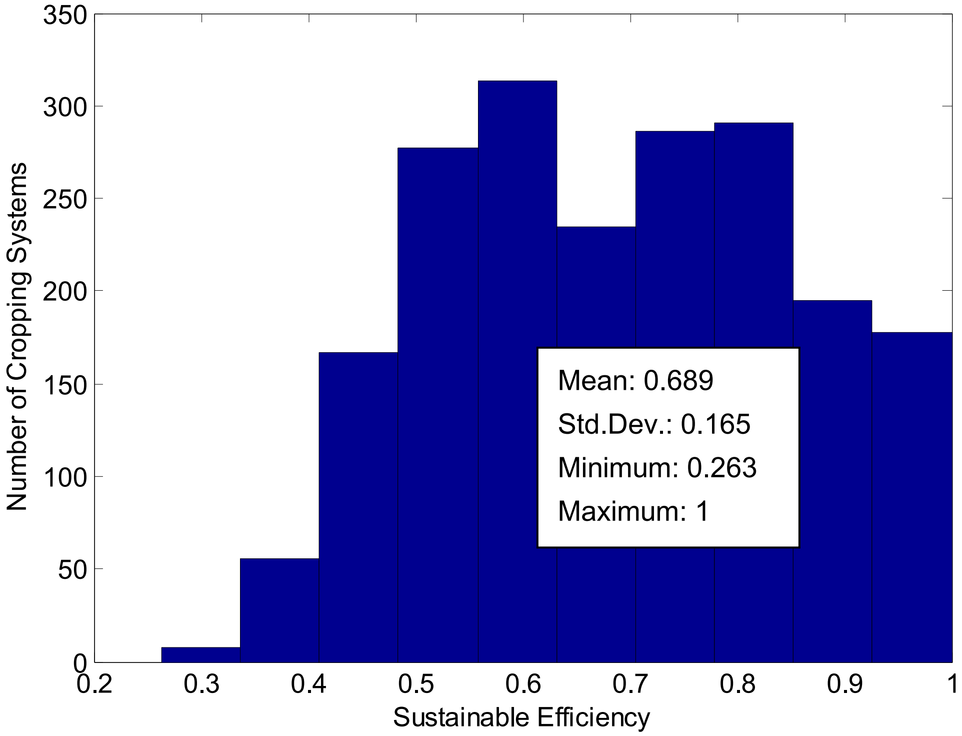

Figure 4.2. Histogram of Sustainable Efficiency for All Cropping Systems

4.4.3 Robustness of the DEA Benchmarks

As discussed in Section 4.2.3, the choice of benchmark is important in calculating sustainable value and sustainable efficiency. To test the robustness of DEA benchmarks in calculating the sustainable value and efficiency (benchmark 1), I compared the results with those calculated by two of the other three benchmarks. The first alternative benchmark is the average of all cropping systems (benchmark 2). The second is using the first observed cropping system, characterized by mono-crop corn, non-mulching, contour, irrigation, human labor and no terracing (benchmark 3). The descriptive statistics of the sustainable efficiency using different benchmarks can be found in Table 4.7. The Spearman's rank correlation of sustainable efficiency using different benchmarks is calculated (Table 4.8), to compare the sustainable efficiency measured by different benchmarks. The correlation between Benchmark 1 and Benchmark 2 is 0.580, and 0.535 between Benchmark 1 and Benchmark 3. This implies that the ranking of the cropping systems was consistent across all three methods, thus supporting the robustness of the DEA benchmark.

Table 4.7. Descriptive Statistics of Sustainable Efficiency Using Different Benchmarks[a]

Sustainable efficiency	Mean	Standard Deviation	Minimum	Maximum
Benchmark 1	0.632	0.180	0.211	1
Benchmark 2	1.229	0.518	0.045	2.827
Benchmark 3	0.791	0.517	0.005	2.648

a-Benchmark 1 = DEA benchmarks; Benchmark 2 = the average of all cropping systems; Benchmark 3 = the first observed cropping system, characterized by mono-crop corn, non-mulching, contouring, irrigation, human labor and no terracing.

Table 4.8. Correlation between the Rankings of Sustainable Efficiency for all 2006 Cropping Systems

	Benchmark 1[a]	Benchmark 2[a]	Benchmark 3[a]
Benchmark 1	1		
Benchmark 2	0.580***	1	
Benchmark 3	0.535***	0.865***	1

Note: *** significant at 1%

a: Benchmark 1= DEA benchmarks; Benchmark 2 = the average cropping system; Benchmark 3 = the first observed cropping system, characterized by mono-crop corn, non-mulching, contouring, irrigation, human labor and no terracing.

4.4.4 Contribution of Conservation Alternatives

4.4.4.1 Regression Results

As shown in Figure 4.1 and Figure 4.2, a large difference in the level of sustainable value and efficiency exists for all cropping systems, which indicates heterogeneity in the sustainable performance of the cropping systems. The sustainable efficiency and sustainable value are regressed on sets of dummy variables to identify the influence of management practices on sustainability. The results are shown in Table 4.9. Before regression pairwise correlations of independent variables are tested. The regressors are only weakly correlated with each other. Heteroskedasticity is rejected at 10% significance level. The regressors are jointly statisctically significant in both models, because the overall F statistics have a p-value of 0. 80.2% of the variation in the sustainable efficiency model is explained by independent variables and 74.6% of in the sustainable value model.

In the sustainable efficiency model, all coefficients are statistically significant at the 10% significance level or better, except for MSC (i.e. millet, soybean, corn) and A3MCPCM (i.e. alfalfa 3 years, millet, corn, potato, corn, millet). All the signs of the coefficients are consistent with expectations. The signs of the coefficients on CSC (i.e. corn, soybean, corn), A3CM (i.e. alfalfa 3 years, corn, millet) and FA5MC (i.e. flax, alfalfa 5 years, millet, corn) are positive, which implies that these three rotations are more sustainable than mono-crop corn. The coefficient in front of mulching is positively significant, which implies compared to non-mulching residue management, mulching contributes some gain in sustainable efficiency. The coefficient in front of contour is negatively significant, which implies that furrow ridging is recommended from the sustainable perspective rather than contouring. The coefficient in front of mechanization is positively significant, which implies that machine intensive cropping systems are more sustainable than labor intensive cropping systems. This might be because machines are more productive and efficient than using labor. Positively significant coefficients in front of bench terrace and spaced terrace implies that they are more sustainable than no terrace. Not surprisingly, cropping systems in the floodplain have higher sustainable efficiency, compared to sloped land.

In the sustainable value model, all the coefficients are statistically significant at 10% significance level except A3CPM, A3MPM, A4MPM, FWA4MC and A3MCPCM (Table 4.9). All the signs of the coefficients are consistent with expectations. CSC (i.e. corn, soybean, corn), MSC (i.e. millet, soybean, corn), A3CM (i.e. alfalfa 3 years, corn, millet) and FA5MC (i.e. flax, alfalfa 5 years, millet, corn) generate 441.2 RMB/ha, 122.4 RMB/ha, 293.4 RMB/ha and 313.4 RMB/ha more sustainable value than mono crop corn. W, PWC, CMP, FWPM, PWCM, WPMCF and MSMP create less sustainable value than corn. Mulching has 468 RMB/ha more sustainable value than non-mulching. Contouring has a 178 RMB/ha less sustainable value than furrow ridging. Rainfed production and N limited production generate 990 and 1970 RMB/ha more sustainable value than irrigation production. Machine intensive cropping systems contributes 1038 RMB/ha more in sustainable value than labor intensive cropping systems. Bench terrace and spaced terrace generate 1178 and 122 RMB/ha more in sustainable value compared to no terrace. Floodplain has the highest sustainable value, compared to the sloped land which has the lowest.

Table 4.9. Estimation Results for the Sustainable Efficiency and Sustainable Value Regression Models

Cropping Systems	Variables[a]	Sustainable Efficiency Model	Sustainable Value Model
		Coefficients	
	Intercept	0.760***	-4867.9***
Rotation (Corn)[b]	W	-0.260***	-465.52***
	PWC	-0.148***	-612.56***
	CMP	-0.172***	-966.38***

	CSC	0.058***	441.16***
	FWPM	-0.271***	-790.35***
	PWCM	-0.155***	-764.61***
	MSC	-0.003	122.41*
	WPMCF	-0.212***	-839.53***
	MSMP	-0.145***	-459.81***
	A3CM	0.039***	293.44***
	A3CPM	-0.018*	8.18
	A3MPM	-0.041***	-55.87
	A4MPM	-0.024***	74.26
	FA5MC	0.027***	313.36***
	FWA4MC	-0.019**	52.31
	A3MCPCM	-0.014	-2.45
Residue (Non-mulching)	Mulching	0.073***	467.96***
Practice (Furrow)	Contour	-0.011***	-178.08***
Production Situation (Irrigation + Abundant N)	Rainfed	0.019*	990.88***
	N-limit	0.098***	1970.07***
Mechanization (Human and Animal Labor)	Mechanization	0.054***	1038.83***
Terracing (No Terrace)	Bench Terrace	0.225***	1178.49***
	Spaced Terrace	0.049***	122.47***
Land Unit (Floodplain)	Gently Sloped	-0.100***	-496.73***
	Moderately Sloped	-0.159***	-771.80***
	Steeply Sloped	-0.191***	-908.10***
	Very Steeply Sloped	-0.218***	-935.08***
Adjusted R-square		0.802	0.746

Note: *** 1% significance level; ** 5% significance level; *1% significance level.

a. A# = alfalfa and years, C = corn, M = millet, F = flax, P = Potato, S = soybean, W = winter wheat.

b. The baseline for each set of dummy variables is shown in the parentheses in Column 1.

4.4.4.2 Sustainable Efficiency and Sustainable Value for All Systems

Three sustainable efficiency matrices for rotation, terrace techniques and land units are created using the estimation results and shown in Table 4.10 to Table 4.12. These tables can be used to compare the sustainable efficiency between all possible pairs of rotation types, terracing techniques and different land units.

The sustainable efficiency matrix for 17 cropping systems is given in Table 4.10. The differences in sustainable efficiency between any two rotations can be found using this matrix.

The rotations in the first row serve as references. For example, a lower sustainable efficiency is created in the cropping systems with W (i.e. wheat) compared to C (i.e. corn). This matrix implies: the CSC (i.e. corn, soybean, corn) rotation has the highest sustainable efficiency among all 17 rotations; A3CM (i.e. alfalfa for 3 years, corn, millet) and FA5MC (i.e. flax, alfalfa for 5 years, millet, corn) rotations rank second. The cropping systems with W (i.e. wheat) and FWPM (i.e. flax, wheat, potato, millet) creates the lowest sustainable efficiency.

The sustainable efficiency matrix for the three terracing techniques (Table 4.11) implies that bench terrace contributes most to sustainable efficiency, followed by spaced terrace. The cropping systems with no terrace had the least sustainable efficiency given all other practices are the same. Not surprisingly, based on the sustainable efficiency matrix for five types of land units (Table 4.12), floodplain is efficient, while very steeply sloped land has the least efficiency.

The same process for comparing practices was repeated for sustainable *value.* The sustainable value matrices for cropping rotation, terracing techniques and types of land units are given in Tables 4.13-4.15. Again, CSC (i.e. corn, soybean, corn) has the most sustainable value, while MSC (i.e. millet, soybean, corn), A3CM (i.e. alfalfa 3 years, corn, millet) and FA5MC (i.e. flax, alfalfa 5 years, millet, corn) rank second. FWPM (i.e. flax, wheat, potato, millet) has the least sustainable value, followed by CMP (i.e. corn, millet, potato) and WPMCF (i.e. wheat, potato, millet, corn, flax). Bench terrace creates 1179 RMB/ha more in sustainable value, compared to no terrace, and 123 RMB/ha more compared to spaced terrace. Floodplain generates 497 RMB/ha more in sustainable value compared to gently sloped land, 772 RMB/ha more compared to moderately steeply sloped land, 908 RMB/ha more compared to steeply sloped land and 935 RMB/ha more compared to very steeply sloped land.

Tables 4.13 to 4.15 show the *statistical* difference in sustainable value between any pair of characters of cropping systems. Small standard errors may associate with a large sample in a regression model, and therefore most of the coefficients are statistically significant. In this case, *economic* significance may be more important than statistical significance. Policy makers can choose appropriate economic differences when making decisions.

Table 4.10. Sustainable Efficiency Matrix for 17 Cropping Rotations

Reference^{a}:	**C**	**W**	**PWC**	**CMP**	**CSC**	**FWPM**	**PWCM**	**MSC**	**WPMCF**	**MSMP**	**A3CM**	**A3CPM**	**A3MPM**	**A4MPM**	**FA5MC**	**FWA4MC**	**A3MCPCM**
C	0																
W	-0.260***	0															
PWC	-0.148***	0.112***	0														
CMP	-0.172***	0.088***	-0.024***	0													
CSC	0.058***	0.318***	0.206***	0.230***	0												
FWPM	-0.271***	-0.011***	-0.123***	-0.099***	-0.329***	0											
PWCM	-0.155***	0.105***	0	0.024*	-0.206***	0.123***	0										
MSC	0	0.260***	0.148***	0.172***	-0.058***	0.271***	0.148***	0									
WPMCF	-0.212***	0.048***	-0.064***	-0.040***	-0.270***	0.059***	-0.064***	-0.212***	0								
MSMP	-0.145***	0.115***	0	0.024***	-0.206***	0.123***	0	-0.148***	0.064***	0							
A3CM	0.039***	0.299***	0.187***	0.211***	-0.019**	0.310***	0.187***	0.039***	0.251***	0.187***	0						
A3CPM	-0.018*	0.242***	0.130***	0.154***	-0.076***	0.253***	0.130***	0	0.212***	0.148***	-0.039***	0					
A3MPM	-0.041***	0.219***	0.107***	0.131***	-0.099***	0.230***	0.107***	-0.041***	0.171***	0.107***	-0.080***	-0.041***	0				
A4MPM	-0.024**	0.236***	0.124***	0.148***	-0.082***	0.247***	0.124***	-0.024**	0.188***	0.124***	-0.063***	0	0.041*	0			
FA5MC	0.027***	0.287***	0.175***	0.199***	-0.031***	0.298***	0.175***	0.027***	0.239***	0.175***	0	0.039***	0.080***	0.063***	0		
FWA4MC	-0.019**	0.241***	0.129***	0.153***	-0.077***	0.252***	0.129***	0	0.212***	0.148***	-0.039***	0	0.041**	0	-0.063***	0	
A3MCPCM	0	0.260***	0.148***	0.172***	-0.058***	0.271***	0.148***	0	0.212***	0.148***	-0.039***	0	0.041***	0	-0.063***	0	0

Note: 0 = no significant difference; * significantly different at 10% level; ** significantly different at 5% level;*** = significantly different at 1% level.

a-A# = alfalfa and years, C = corn, M = millet, F = flax, P = potato, S = soybean, W = winter wheat.

Table 4.11. Sustainable Efficiency Matrix for 3 Terracing Techniques

Reference:	No Terracing	Bench Terrace	Spaced Terrace
No Terracing	0		
Bench Terrace	0.225***	0	
Spaced Terrace	0.049***	-0.176***	0

Note: 0 = no significant difference; * significantly different at 10% level;** significantly different at 5% level;*** = significantly different at 1% level.

Table 4.12. Sustainable Efficiency Matrix for 5 Types of Land Units

Reference:	Floodplain	Gently	Moderately	Steeply	Very Steeply
Floodplain	0				
Gently[a]	-0.100***	0			
Moderately	-0.159***	-0.059***	0		
Steeply	-0.191***	-0.091***	-0.032***	0	
Vey Steeply	-0.218***	-0.118***	-0.059***	-0.027***	0

Note: *** denotes significant at 1% significance level; ** 5% significance level; *10% significance level. a-Gently = gently sloped land; Moderately = moderately sloped land; Steeply = steeply sloped land; Very Steeply = very steeply sloped land.

Table 4.13. Sustainable Value Matrix for 17 Cropping Rotations (RMB/ha)

Reference[a]:	**C**	**W**	**PWC**	**CMP**	**CSC**	**FWPM**	**PWCM**	**MSC**	**WPMCF**	**MSMP**	**A3CM**	**A3CPM**	**A3MPM**	**A4MPM**	**FA5MC**	**FWA4MC**	**A3MCPCM**
C	0																
W	-465.52***	0															
PWC	-612.56***	-147.04**	0														
CMP	-966.38***	-500.86***	-353.82***	0													
CSC	441.16***	906.68***	1053.72***	1407.54***	0												
FWPM	-790.35***	-324.83***	-177.79***	176.03***	-1231.51***	0											
PWCM	-764.61***	-299.09***	-152.05**	201.77***	-1205.77***	0	0										
MSC	122.41***	587.93***	734.97***	1088.79***	-318.75***	912.76***	912.76***	0									
WPMCF	-839.53***	-374.01***	-226.97***	126.85*	-1280.69***	0	0	-912.76***	0								
MSMP	-459.81***	0	147.04**	500.86***	-906.68***	324.83***	324.83***	-587.93***	324.83***	0							
A3CM	293.44***	758.96***	906.00***	1259.82***	-147.72**	1083.79***	1083.79***	171.03***	1083.79***	758.96***	0						
A3CPM	0	465.52***	612.56***	966.38***	-441.16***	790.35***	790.35***	-122.41**	790.35***	465.52***	-293.44***	0					
A3MPM	0	465.52***	612.56***	966.38***	-441.16***	790.35***	790.35***	-122.41***	790.35***	465.52***	-293.44***	0.00	0				
A4MPM	0	465.52***	612.56***	966.38***	-441.16***	790.35***	790.35***	0	912.76***	587.93***	-171.03***	0.00	0.00	0			
FA5MC	313.36***	778.88***	925.92***	1279.74***	-127.80*	1103.71***	1103.71***	190.95***	1103.71***	778.88***	0	293.44***	293.44***	293.44***	0		
FWA4MC	0	465.52***	612.56***	966.38***	-441.16***	790.35***	790.35***	0	912.76***	587.93***	-171.03***	0	0	0	-293.44***	0	
A3MCPCM	0	465.52***	612.56***	966.38***	-441.16***	790.35***	790.35***	-122.41*	790.35***	465.52***	-293.44***	0	0	0	-293.44***	0	0

Note: 0 = no significant difference; * significantly different at 10% level; ** significantly different at 5% level;*** = significantly different at 1% level.

a- A# = alfalfa and years, C = corn, M = millet, F = flax, P = potato, S = soybean, W = winter wheat.

Table 4.14. Sustainable Value Matrix for 3 Terracing Techniques (RMB/ha)

Reference:	No Terracing	Bench Terrace	Spaced Terrace
No Terracing	0		
Bench Terrace	1178.5***	0	
Spaced Terrace	122.5***	1056***	0

Note: 0 = no significant difference; * significantly different at 10% level;** significantly different at 5% level;*** = significantly different at 1% level.

Table 4.15. Sustainable Value Matrix for 5 Types of Land Units (RMB/ha)

Reference:	Floodplain	Gently	Moderately	Steeply	Vey Steeply
Floodplain	0				
Gently[a]	-496.7***	0			
Moderately	-771.8***	-275.1***	0		
Steeply	-908.1***	-411.4***	-136.3***	0	
Vey Steeply	-935.1***	-438.4***	-163.3***	-27.0***	0

Note: *** denotes significant at 1% significance level; ** 5% significance level; *10% significance level. a-Gently = gently sloped land; Moderately = moderately sloped land; Steeply = steeply sloped land; Very Steeply = very steeply sloped land.

4.5 Conclusions and Discussions

Sustainable development in agriculture is regarded as an ultimate and strategic goal for the ecologically fragile Loess Plateau of China. Allocating resources efficiently is a necessary step toward achieving sustainability. Sustainability is a complex concept including economic, environmental and social aspects. To cope with the multidimensionality of sustainability, as much economic, environmental and social information should be taken into account as possible when designing the sustainable indicator.

Many different indicators have been developed to assess sustainability. The sustainable value approach was developed by Figge and Hahn to calculate sustainable value and sustainable efficiency. Sustainable value is a monetary measurement of sustainability in dollars. It offers sustainable information to policy makers in dollars, which can easily be compared with other values in the same units. It also makes it convenient for different interest groups to discuss sustainability. Sustainable efficiency is a normalized measurement of sustainability. The sustainable efficiency score of 1 implies the most efficient, while zero means the least.

The sustainable value approach allows flexibility in choosing a benchmark to reflect a policy judgment or objective. Different from the previous literature, I proposed a DEA method to construct the best-performance benchmark, called DEA benchmarks. The cropping systems that lie on the production frontier are a set of best performing benchmarks. The DEA benchmark is attractive, because it takes the production possibilities into account, and assigns each firm a unique benchmark. It also improves upon the parametric frontier benchmark proposed by Van Passel et al. (2009), since the DEA approach avoids the functional form specification error, is much easier to compute, and does not require a large dataset. The DEA benchmark used here was verified to be robust by comparing it to other benchmarks.

Various cropping practices allocate the resources differently. It is important for farmers and policy makers to analyze the marginal contributions of alternative cropping techniques, and identify the most sustainable cropping systems. Farmers can use this information for guidance to direct their practice choices. For example, farmers may have no idea about how much benefits they can gain by switching from non-mulching to mulching. The sustainable value approach can answer their questions in monetary terms. In poor areas of China, farmers may lack knowledge about advanced cropping practices. The government can help farmers switch from unsustainable to sustainable cropping systems, by subsidizing or offering technology support. The sustainable value approach provides an approximation of the amount of subsidy required and specifies the technology information. For example, 441 RMB/ha in sustainable value will be gained if the mono-crop corn is switched to the corn-soybean-corn rotation. Farmers may not have this knowledge, and therefore the government can implement some conservation programs to direct farmers’ behavior. There will be a net welfare gain if the programs cost less than 441 RMB/ha.

In this chapter I first calculated the sustainable value and sustainable efficiency for over 2000 possible cropping systems in the Loess Plateau, using the sustainable value approach with the updated DEA benchmark. Marginal contributions of alternative cropping practices are explained by a regression model, and the most sustainable cropping systems are identified. Finally, several sustainable value matrices and sustainable efficiency matrices are provided to compare any pair of cropping practices. The conclusions are as follows:

(1) The mean of sustainable value and sustainable efficiency for all the 2006 cropping systems are –1661 RMB/ha and 0.689. On average, the sustainable performance can be improved by allocating resources more efficiently.

(2) The sustainable value and sustainable efficiency matrices for cropping rotations are created. Any two rotations types can be compared easily from a sustainability perspective. The CSC (i.e. corn, soybean, corn) rotation has the highest sustainable value and efficiency among all 17 rations options, followed by A3CM (i.e. alfalfa 3 years, corn, millet) and FA5MC (flax, alfalfa 5 years, millet, corn). FWPM (i.e. flax, wheat, potato, millet) has the least sustainable efficiency score, while WPMCF (wheat, potato, millet, corn, flax) has the least sustainable value.

(3) The sustainable value and efficiency matrices for terracing techniques and land units are also created. Bench terrace generates the most sustainable value and produces the highest sustainable efficiency. Not surprisingly, the sustainable value and efficiency with floodplain are higher than sloped lands.

(4) Cropping systems with crop mulching, furrow ridging and intensive mechanization level are more sustainable than those with non-mulching, contouring and lower mechanization level, respectively.

(5) The machine intensive cropping system characterized by rotation CSC (i.e. corn, soybean, corn) with mulching, furrow ridging, and bench terracing in floodplain has the most sustainable efficiency.

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APPENDIX 1

MATLAB CODE FOR CHAPTER 2

```
% DEMDP00 Soil Management Model0: Private Model
  disp('DEMDP00 Soil MANAGEMENT MODEL')
  close all

% ENTER MODEL PARAMETERS
  a = [3 36.44 47.01 -0.09864 5 40];
        % production function: a1=price; yield(bu/ha)=a2+a3*(1-
          e^a4*depth(inch))
        % externality: a5*(a4-s)^2;
  b = [-1.1372 0.0364];
        % cost function: C(R)=10^(b1+b2*R),R=0-100(%)
  c = [-1.5 10 -0.013];
        % transition function: s=s-c1*c2^(c3*x)
  delta = 0.95;
        % discount factor

% PACK MODEL STRUCTURE
  clear model0
  model0.func = 'mfdp00830';                % model function file
  model0.discount = delta;                  % discount factor
  model0.params = {a b c};                  % other parameters

% DEFINE APPROXIMATION SPACE
  n0    = 500;                                  % degree of approximation
  smin0 =  0;                                   % minimum state:depth=0inch
  smax0 =  40;                                  % maximum state:denpth=40inch
  fspace0 = fundefn('spli',n0,smin0,smax0);     % function space
  snodes0 = funnode(fspace0);                   % state collocaton nodes

% INITIALIZE POLICY and VALUE FUNCTIONS
  xinit0 = zeros(size(snodes0));                    % initial policy function
  vinit0 = zeros(size(snodes0));                    % initial value function

% CHECK MODEL DERIVATIVES AT CE STEADY STATE
  err0=dpcheck(model0,(smin0+smax0)/2,0);

% SOLVE BELLMAN EQUATION
  [cc0,s0,v0,x0] = dpsolve(model0,fspace0,snodes0,vinit0,xinit0);

% PLOT OPTIMAL POLICY
  figure(1);
  plot(s0,x0,'k');
  title('Optimal Soil Management Policy');
  xlabel('Soil Depth (in.)');
  ylabel('Crop Residue Management(%)');
  hold all;

 % PLOT VALUE FUNCTION
  figure(2);
```

```
  plot(s0,v0,'k');
  title('Value Function');
  xlabel('Soil Depth(in.)');
  ylabel('Value($)');
  hold all;

% PLOT SHADOW PRICE FUNCTION
  figure(3);
  p0 = funeval(cc0,fspace0,s0,1);
  plot(s0,p0,'k');
  title('Shadow Price Function');
  xlabel('Soil Depth');
  ylabel('Price');
  xlim([0 40]);
  hold all;

% COMPUTE STATE AND POLICY PATH
  nyrs0 = 30;
  sinit0 = smax0;
  [spath0,xpath0] = dpsimul(model0,sinit0,nyrs0,s0,x0);

% PLOT STATE PATH
  figure(4);
  plot(0:nyrs0,spath0,'k');
  title('Soil Depth Path');
  xlabel('Year');
  ylabel('Soil Depth');
  hold all;

% PLOT POLICY PATH
  figure(5);
  plot(0:nyrs0,xpath0,'k');
  title('Crop Residue Management Path');
  xlabel('Year');
  ylabel('Residue Management');
  hold all;

% PLOT Farm Profit
  figure(6);
  profit0 = a(1)*(a(2)+a(3)*(1-exp(a(4).*spath0)))-
(10.^(b(1)+b(2).*xpath0)).*xpath0;
  plot(0:nyrs0,profit0,'k');
  title('Farm Profit Model 0');
  xlabel('Year');
  ylabel('Farm Profit');
  hold all;

% PLOT WELFARE
  figure(7);
  welfare0 = (a(1)+2)*(a(2)+a(3).*(1-exp(a(4).*spath0)))...
      -(10.^(b(1)+b(2).*xpath0)).*xpath0-a(5).*(a(6)-spath0);
  plot(0:nyrs0,welfare0,'k');
  title('Total Welfare Model 0');
  xlabel('Year');
  ylabel('Welfare');
  hold all;
```

```
  % PLOT Production
  figure(8);
  prod0=a(2)+a(3)*(1-exp(a(4).*spath0));
  plot(0:nyrs0,prod0,'k');
  title('Production');
  xlabel('Year');
  ylabel('Production');
  hold all;

%% Model 1: Only externality
% PACK MODEL STRUCTURE
  clear model1
  model1.func = 'mfdp00831';                  % model function file
  model1.discount = delta;                    % discount factor
  model1.params = {a b c};                    % other parameters

% DEFINE APPROXIMATION SPACE
  n1    = 500;                               % degree of approximation
  smin1 =  0;                                % minimum state:depth=0inch
  smax1 =  40;                               % maximum state:denpth=40inch
  fspace1 = fundefn('spli',n1,smin1,smax1);  % function space
  snodes1 = funnode(fspace1);                % state collocaton nodes

% INITIALIZE POLICY and VALUE FUNCTIONS
  xinit1 = zeros(size(snodes1));                 % initial policy function
  vinit1 = zeros(size(snodes1));                 % initial value function

% CHECK MODEL DERIVATIVES AT CE STEADY STATE
  err1=dpcheck(model1,(smin1+smax1)/2,0);

% SOLVE BELLMAN EQUATION
  [cc1,s1,v1,x1] = dpsolve(model1,fspace1,snodes1,vinit1,xinit1);

% PLOT OPTIMAL POLICY
  figure(1);
  plot(s1,x1,'.-r');
  title('Optimal Soil Management Policy');
  xlabel('Soil Depth (in.)');
  ylabel('Crop Residue Management(%)');
  hold all;

% PLOT VALUE FUNCTION
  figure(2);
  plot(s1,v1,'.-r');
  title('Value Function');
  xlabel('Soil Depth(in.)');
  ylabel('Value($)');
  hold all;

% PLOT SHADOW PRICE FUNCTION
  figure(3);
  p1 = funeval(cc1,fspace1,s1,1);
  plot(s1,p1,'.-r');
  title('Shadow Price Function');
  xlabel('Soil Depth');
```

```
  ylabel('Price');
  xlim([0 40]);
  hold all;

% COMPUTE STATE AND POLICY PATH
  nyrs1 = 30;
  sinit1 = smax1;
  [spath1,xpath1] = dpsimul(model1,sinit1,nyrs1,s1,x1);

% PLOT STATE PATH
  figure(4);
  plot(0:nyrs1,spath1,'.-r');
  title('Soil Depth Path');
  xlabel('Year');
  ylabel('Soil Depth');
  hold all;

% PLOT POLICY PATH
  figure(5);
  plot(0:nyrs1,xpath1,'.-r');
  title('Crop Residue Management Path');
  xlabel('Year');
  ylabel('Residue Management');
  hold all;

% PLOT Farm Profit
  figure(6);
  profit1 = a(1)*(a(2)+a(3)*(1-exp(a(4).*spath1)))-
(10.^(b(1)+b(2).*xpath1)).*xpath1;
  plot(0:nyrs1,profit1,'.-r');
  title('Farm Profit Model');
  xlabel('Year');
  ylabel('Farm Profit');
  hold all;

% PLOT WELFARE
  figure(7);
  welfare1 = (a(1)+2)*(a(2)+a(3).*(1-exp(a(4).*spath1)))...
      -(10.^(b(1)+b(2).*xpath1)).*xpath1-a(5).*(a(6)-spath1);
  plot(0:nyrs1,welfare1,'.-r');
  title('Total Welfare Model 0');
  xlabel('Year');
  ylabel('Welfare');
  hold all;

% PLOT production
  figure(8);
  prod1=a(2)+a(3)*(1-exp(a(4).*spath1));
  plot(0:nyrs1,prod1,'.-r');
  title('Production');
  xlabel('Year');
  ylabel('Production');
  hold all;
```

```
%% Model 2: Only food security
% PACK MODEL STRUCTURE
  clear model2
  model2.func = 'mfdp00832';                 % model function file
  model2.discount = delta;                % discount factor
  model2.params = {a b c};                % other parameters

% DEFINE APPROXIMATION SPACE
  n2    = 500;                            % degree of approximation
  smin2 =  0;                             % minimum state:depth=0inch
  smax2 =  40;                            % maximum state:denpth=40inch
  fspace2 = fundefn('spli',n2,smin2,smax2);  % function space
  snodes2 = funnode(fspace2);              % state collocaton nodes

% INITIALIZE POLICY and VALUE FUNCTIONS
  xinit2 = zeros(size(snodes2));                 % initial policy function
  vinit2 = zeros(size(snodes2));                  % initial value function

% CHECK MODEL DERIVATIVES AT CE STEADY STATE
  err2=dpcheck(model2,(smin2+smax2)/2,0);

% SOLVE BELLMAN EQUATION
  [cc2,s2,v2,x2] = dpsolve(model2,fspace2,snodes2,vinit2,xinit2);

% PLOT OPTIMAL POLICY
  figure(1);
  plot(s2,x2,':g');
  title('Optimal Soil Management Policy');
  xlabel('Soil Depth (in.)');
  ylabel('Crop Residue Management(%)');
  hold all;

% PLOT VALUE FUNCTION
  figure(2);
  plot(s2,v2,':g');
  title('Value Function');
  xlabel('Soil Depth(in.)');
  ylabel('Value($)');
  hold all;

% PLOT SHADOW PRICE FUNCTION
  figure(3);
  p2 = funeval(cc2,fspace2,s2,1);
  plot(s2,p2,':g');
  title('Shadow Price Function');
  xlabel('Soil Depth');
  ylabel('Price');
  xlim([0 40]);
  hold all;

% COMPUTE STATE AND POLICY PATH
  nyrs2 = 30;
  sinit2 = smax2;
  [spath2,xpath2] = dpsimul(model2,sinit2,nyrs2,s2,x2);
```

```
% PLOT STATE PATH
  figure(4);
  plot(0:nyrs2,spath2,':g');
  title('Soil Depth Path');
  xlabel('Year');
  ylabel('Soil Depth');
  hold all;

% PLOT POLICY PATH
  figure(5);
  plot(0:nyrs2,xpath2,':g');
  title('Crop Residue Management Path');
  xlabel('Year');
  ylabel('Residue Management');
  hold all;

% PLOT Farm Profit
  figure(6);
  profit2 = a(1)*(a(2)+a(3)*(1-exp(a(4).*spath2)))-
(10.^(b(1)+b(2).*xpath2)).*xpath2;
  plot(0:nyrs2,profit2,':g');
  title('Farm Profit Model');
  xlabel('Year');
  ylabel('Farm Profit');
  hold all;

% PLOT WELFARE
  figure(7);
  welfare2 = (a(1)+2)*(a(2)+a(3).*(1-exp(a(4).*spath2)))...
      -(10.^(b(1)+b(2).*xpath2)).*xpath2-a(5).*(a(6)-spath2);
  plot(0:nyrs2,welfare2,':g');
  title('Total Welfare Model 0');
  xlabel('Year');
  ylabel('Welfare');
  hold all;

% PLOT production
  figure(8);
  prod2=a(2)+a(3)*(1-exp(a(4).*spath2));
  plot(0:nyrs2,prod2,':g');
  title('Production');
  xlabel('Year');
  ylabel('Production');
  hold all;

%% Model 3: Both Food Security and Externality

% PACK MODEL STRUCTURE
  clear model3
  model3.func = 'mfdp00833';                     % model function file
  model3.discount = delta;                  % discount factor
  model3.params = {a b c};                  % other parameters

% DEFINE APPROXIMATION SPACE
  n3    = 500;                              % degree of approximation
```

```
  smin3 =  0;                             % minimum state:depth=0inch
  smax3 =  40;                            % maximum state:denpth=40inch
  fspace3 = fundefn('spli',n3,smin3,smax3);  % function space
  snodes3 = funnode(fspace3);              % state collocaton nodes

% INITIALIZE POLICY and VALUE FUNCTIONS
  xinit3 = zeros(size(snodes3));                 % initial policy function
  vinit3 = zeros(size(snodes3));                  % initial value function

% CHECK MODEL DERIVATIVES AT CE STEADY STATE
  err3=dpcheck(model3,(smin3+smax3)/2,0);

% SOLVE BELLMAN EQUATION
  [cc3,s3,v3,x3] = dpsolve(model3,fspace1,snodes3,vinit3,xinit3);

% PLOT OPTIMAL POLICY
  figure(1);
  plot(s3,x3,'--b');
  title('Optimal Soil Management Policy');
  xlabel('Soil Depth (in.)');
  ylabel('Crop Residue Management(%)');
  hold all;

% PLOT VALUE FUNCTION
  figure(2);
  plot(s3,v3,'--b');
  title('Value Function');
  xlabel('Soil Depth(in.)');
  ylabel('Value($)');
  hold all;

% PLOT SHADOW PRICE FUNCTION
  figure(3);
  p3 = funeval(cc3,fspace3,s3,1);
  plot(s3,p3,'--b');
  title('Shadow Price Function');
  xlabel('Soil Depth');
  ylabel('Price');
  xlim([0 40]);
  hold all;

% COMPUTE STATE AND POLICY PATH
  nyrs3 = 30;
  sinit3 = smax3;
  [spath3,xpath3] = dpsimul(model3,sinit3,nyrs3,s3,x3);

% PLOT STATE PATH
  figure(4);
  plot(0:nyrs3,spath3,'--b');
  title('Soil Depth Path');
  xlabel('Year');
  ylabel('Soil Depth');
  hold all;
```

```
% PLOT POLICY PATH
  figure(5);
  plot(0:nyrs3,xpath3,'--b');
  title('Crop Residue Management Path');
  xlabel('Year');
  ylabel('Residue Management');
  hold all;

% PLOT FARM PROFIT
  figure(6);
  profit3 = a(1)*(a(2)+a(3)*(1-exp(a(4).*spath3)))-
(10.^(b(1)+b(2).*xpath3)).*xpath3;
  plot(0:nyrs3,profit3,'--b');
  title('Farm Profit Model');
  xlabel('Year');
  ylabel('Farm Profit');
  hold all;

% PLOT WELFARE
  figure(7);
  welfare3 = (a(1)+2)*(a(2)+a(3).*(1-exp(a(4).*spath3)))...
      -(10.^(b(1)+b(2).*xpath3)).*xpath3-a(5).*(a(6)-spath3);
  plot(0:nyrs3,welfare3,'--b');
  title('Total Welfare Model 0');
  xlabel('Year');
  ylabel('Welfare');
  hold all;

% PLOT PRODUCTION
  figure(8);
  prod3=a(2)+a(3)*(1-exp(a(4).*spath3));
  plot(0:nyrs3,prod3,'--b');
  title('Production');
  xlabel('Year');
  ylabel('Production');
  hold all;
```

APPENDIX 2

MATLAB CODING FOR CHAPTER 3

```
%% CHAPTER 3: x produces y1(crop), y2(nitrogen)and y3(soil).
%newdata/Orig June 1st

%% Import Data
OrigX=Orig(:,1);
OrigY1=Orig(:,2);
OrigY2=Orig(:,3);
OrigY3=Orig(:,4);

Bar=sum(Orig)/1720;

xx=OrigX/Bar(1,1);
y1=OrigY1/Bar(1,2);
y2=OrigY2/Bar(1,3);
y3=OrigY3/Bar(1,4);

basic=[ones(1720,1) xx y1 y2 y3 0.5*xx.*xx 0.5*y1.*y1 0.5*y2.*y2 0.5*y3.*y3...
   0.5*y2.*y3 0.5*y3.*y2 xx.*y1 xx.*y2 xx.*y3 y1.*y2 y1.*y3];

% Descriptive Statistics
[MeanA StdA MinA
MaxA]=grpstats(basic(:,2:5),basic(:,1),{'mean','std','min','max'});
StatSumA=vertcat(MeanA,StdA,MinA,MaxA);

[Mean Std Min Max]=grpstats([OrigX OrigY1 OrigY2
OrigY3],basic(:,1),{'mean','std','min','max'});
StatSum=vertcat(Mean,Std,Min,Max);
%% Linear Inequality

% Inequality 1-D>0
basicneg=-basic;

% Inequality 1-D/y1<0

gradient1=[zeros(1720,2) ones(1720,1) zeros(1720,3) y1 zeros(1720,4) xx
zeros(1720,2) y2 y3];

% Inequality 2-D/y2>0
gradient2=[zeros(1720,3) ones(1720,1) zeros(1720,3) y2 zeros(1720,1) 0.5*y3
0.5*y3 zeros(1720,1) xx zeros(1720,1) y1 zeros(1720,1)];

gradient2neg=-gradient2;

% Inequality 3-D/y3>0
gradient3=-[zeros(1720,4) ones(1720,1) zeros(1720,3) y3 0.5*y2 0.5*y2
zeros(1720,2) xx zeros(1720,1) y1];

gradient3neg=-gradient3;
```

```
 % Inequality 4-D/x>0
gradient4=[zeros(1720,1) ones(1720,1) zeros(1720,3) xx zeros(1720,5) y1 y2 y3
zeros(1720,2)];
gradient4neg=-gradient4;


% sum inequality
A=vertcat(basicneg,gradient1,gradient2neg,gradient3neg,gradient4neg);
b=zeros(1720*5,1);

%% Equality total=6
beq1=-ones(1,1);
beq2=zeros(5,1);
beq=vertcat(beq1,beq2);

% Equality 1
Aeq1=[0 0 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0];

Aeq2=[0 0 0 0 0 0 1 0 0 0 0 0 0 0 -1 -1];

Aeq3=[0 0 0 0 0 0 0 1 0 1 0 0 0 0 -1 0];

Aeq4=[0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 -1];

Aeq5=[0 0 0 0 0 0 0 0 0 0 0 1 -1 -1 0 0];

Aeq6=[0 0 0 0 0 0 0 0 0 1 -1 0 0 0 0 0];

Aeq=vertcat(Aeq1,Aeq2,Aeq3,Aeq4,Aeq5,Aeq6);

%% Objective Function
f=sum(basic);
[x,fval,exitflag,output]=linprog(f,A,b,Aeq,beq,[],[],[]);

%% Calculate Distance Function
D=basic*x;

DStatSum=[mean(D) std(D) min(D) max(D)];

Dy1=gradient1*x;
Dy2=gradient2*x;
Dy3=gradient3*x;

p2=Dy2./Dy1;
p3=Dy3./Dy1;

pp2=-p2;
pp3=-p3;

%% Marginal Abatement Cost
% MAC for nitrogen
%Tier1
mac2=[OrigY2 pp2];
```

```
mac2f1=[zeros(1720,1) mac2];
for i=1:1720;
  for j=1:1720;
    if  mac2(j,1)>mac2(i,1);
        if mac2(j,2)<mac2(i,2);
            mac2f1(i,:)=[i 0 0];
        else mac2f1(i,1)=i;
        end
    end
  end
end



% MAC for soil, tier 1
mac3=[OrigY3 pp3];% MAC for soil
mac3f1=[zeros(1720,1) mac3]; % Tier 1
for i=1:1720;
    for j=1:1720;
        if mac3(j,1)<mac3(i,1);
            if mac3(j,2)<mac3(i,2);
                mac3f1(i,:)=[i 0 0];
            else mac3f1(i,1)=i;
            end
        end
    end
end



% Calculate TAC for 1720 cropping sys.
% dominant cropping systems
tacsoil=101.43*OrigY3./1000-0.7*(OrigY3./1000).^2;
tacnitro=0.212*OrigY2+(0.0002757/3)*OrigY2.^3;
tacsn=tacsoil+tacnitro;

% all cropping systems
tacsoil1=106.88*(OrigY3./1000)-0.725*(OrigY3./1000).^2;
tacnitro1=0.2927*OrigY2+(0.0002706)*OrigY2.^3;
tacsn1=tacsoil1+tacnitro1;

ratio=tacsn./OrigY1;

% Calculate Environment-adjusted Farm Profit (EFP)
EFP=OrigY1-OrigX-tacsn;
```

APPENDIX 3

MATLAB CODING FOR CHAPTER 4

```
%% Chapter4-Input distance function
% redefine "basic", revenue-soil-nitrogen-capital-labor
lb=zeros(2007,1);
A1=zeros(5,1);
A21=-basic(:,1)';
A22=basic(:,2:5)';
A2=vertcat(A21,A22);
A=horzcat(A1,A2);
b=zeros(5,1);
f=[1 zeros(1,2006)];

k=zeros(2006,1);
for i=1:2006;
    A(2:5,1)=-basic(i,2:5)';
    b(1,1)=-basic(i,1);
[x,fval,exitflag,output]=linprog(f,A,b,[],[],lb,[],[],optimset('Display','ite
r','MaxIter',1e+8,'LargeScale','off','Simplex', 'on'));
k(i,1)=x(1,1);
end;

d=1./k; % distance function value

effsoil=basic(:,2).*k;
effnitrogen=basic(:,3).*k;
effcapital=basic(:,4).*k;
efflabor=basic(:,5).*k;

profit=basic(:,1)-basic(:,4);
soil=basic(:,2);
nitrogen=basic(:,3);
capital=basic(:,4);
labor=basic(:,5);

% capital cost= cc
ccsoil=profit./effsoil;
ccnitrogen=profit./effnitrogen;
cccapital=profit./effcapital;
cclabor=profit./efflabor;

svsoil=profit./(soil+0.001)-profit./(effsoil+0.001);
svnitrogen=profit./nitrogen- profit./effnitrogen;
svcapital=profit./capital-profit./effcapital;
svlabor=profit./labor-profit./efflabor;

sustain=(1/4)*(svsoil.*soil+svnitrogen.*nitrogen...
    +svlabor.*labor);
 sustaineff=profit./(profit-sustain);
```