THREE ESSAYS ON AGRICULTURAL AND FORESTRY OFFSETS IN CLIMATE CHANGE MITIGATION

A Dissertation

by

SIYI FENG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2012

Major Subject: Agricultural Economics

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Approved by:

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ABSTRACT

Three Essays On Agricultural and Forestry Offsets In Climate Change Mitigation.

(May 2012)

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Chair of Advisory Committee: Dr. Richard T. Woodward

This dissertation is composed of three essays, investigating two aspects of the role of agricultural sector in climate change mitigation: *leakage* and *additionality*.

Leakage happens when mitigation policies reduce net GHG emissions in one context, but increase (decrease) prices, which in turn causes production (demand) expansion resulting in an offsetting rise in emissions elsewhere. The first essay documents an integration of a US domestic agricultural sectoral model and a global agricultural sectoral model, with the aim to deliver better leakage assessment. The second essay investigates the trend of US crop yield growth and its implication on the international leakage effect. We find that the slowdowns have occurred to the growth rates of most US major crops. The implementation of climate change mitigation strategies, such as the expansion of bioenergy production, causes demand for the agricultural sector to increase substantially. The new demand would cause noticeable leakage effect if crop yields continue to grow at the current rates. Such effect may be

potentially alleviated by higher crop yield growth rates; but the extent of alleviation depends on the mix of technological progress obtained across crops as well.

Additionality is often a concern in programs designed to incentivize the production of environmental services. Additionality is satisfied if payments are made to services that would not have occurred without the payment. However, because of the information asymmetry between service buyers and sellers, ensuring additionality poses a challenge to program designers. The third essay investigates how the pursuit of ensuring additionality would complicate environmental policy design with a theoretical model. Specifically, we examine 4 types of policy design, including 2 discriminating schemes and 2 simpler non-discriminating schemes. We found that under certain conditions, some of the non-discriminating schemes can be almost as good as the discriminating ones.

Findings in this dissertation contribute to inform policy makers about the potential impacts of climate change mitigation policies in the agricultural sector and also help to improve understanding of environmental program design.

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CHAPTER I

INTRODUCTION

There is growing international consensus that the atmospheric greenhouse gas (GHG) concentrations need to be stabilized at a level that would prevent dangerous anthropogenic interference with the climate system (IPCC 2007). In the suite of climate change mitigation policies, the agricultural sector (in a broad sense that includes forestry) is expected to play an important role, especially in the near future when low cost mitigation technology in the energy sector is still under development. The agricultural sector is both an emitter and a sink of GHG. On one hand, deforestation, mostly caused by agricultural land expansion, counts for about 17% annual GHG emissions (IPCC 2007) and emissions from fertilizer use and livestock production are also non-negligible. On the other hand, the agricultural sector contributes to climate change mitigation in both indirect ways, such as producing feedstock for bioenergy to displace fossil fuel, and direct ways, such as to sequester carbon through practice and land use change. To make the agricultural sector a net sink of GHG, policies need to be properly designed. This dissertation is devoted to two issues in realizing the mitigation opportunities in the agricultural sector: *leakage* and *additionality*.

Leakage happens when mitigation policies reduce net GHG emissions in one context, but increase prices, which in turn causes production expansion resulting in an

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This dissertation follows the style of the *American Journal of Agricultural Economics*.

offsetting rise in emissions elsewhere. The global concern of leakage is raised by the rapid growth in bioenergy production. In the past decade, US corn usage for ethanol has risen from 15.9 million tons (less than 5% of the total crop) to 104 million tons (almost 40%), causing crop prices to increase substantially (Trostle 2008, Abbott, Hurt and Tyner 2009). Stimulated by higher prices, corn production in the US has expanded by 40% in the same period, both due to changes on the extensive margin (e.g., expansion of cropland via clearing of grassland, unprotected forest) resulting in 11% more corn acreage, and on the intensive margin (e.g. using improved seeds to increase yield) (Melillo, et al. 2009). As the agricultural market is essentially international in nature, substantial production expansion may have happened outside of the country boarder as well. Production expansion in the form of indirect land use change is of particular concern as large amount of carbon is currently sequestered on the potential arable land. Clearance of these lands would result in substantial GHG emissions, offsetting the benefits of bioenergy use.

The magnitude of leakage is subject to careful scrutinization in existing literature. However, estimates vary widely between large and small, depending on model assumptions and values of key parameters used (Keeney and Hertel 2009, Schneider and McCarl 2006, EPA 2010). Assessment of indirect land use change (ILUC) and leakage is possible only when both the international effect of one country's policy including any land use change plus adjustments in the country can be captured in the model. The first essay of this dissertation (Chapter II) makes a contribution to this discussion by developing of a global partial-equilibrium agricultural sector model with a detailed US component.

The second essay (Chapter III) explicitly addresses the issue of leakage, but is further motivated by the concern of slowdown in productivity of the US agricultural sector, especially the crop yield growth rates. Crop yield growth rates are a key factor in determining whether growing demand can be met without expanding the land base and therefore also the leakage effect. This essay is devoted to estimating the US crop yield growth trend over the past 70 years and test for existence of slowdowns. And the model developed in the first essay is applied to investigate the implications of technology progress on the international effect of US bioenergy policy.

In the last essay (Chapter IV) we turn our attention to the issue of additionality. Most actual and proposed schemes to induce climate change mitigation involve a cap-and-trade schemes that have geographical and sectoral coverage limits, oftentimes accompanied by an *offset* component that allows the capped sectors satisfy their obligations by paying uncapped sources to reduce their emissions. The environmental integrity of such programs requires that additionality be satisfied. In other words, the reductions have to be those that would not have been generated without payment. However, in reality, it is very difficult to weed out non-additional reductions from additional reductions because of problems of asymmetric information. The concern of additionality is prevalent in all kinds of payment for environmental service programs. The last essay is devoted to examine how to achieve additionality in policy design with a theoretical model. Specifically, four contract designs, including the second best screening-contract and the often discussed baseline method, are investigated in the situation in which the service buyer knows the existence but not the specific sources of the non-additional services and aims to minimize the costs of procuring given amount of additional environmental services.

CHAPTER II

INTEGRATION OF FASOM AND GLOBIOM

1. Introduction

The development of bioenergy is proceeding around the world for at least four reasons: energy security, low costs compared to fossil fuel prices, policy incentives and climate change mitigation benefits. The US is the largest ethanol producer and continues to promote biofuel use through polices, such as the Renewable Fuel Standard and blender's credit subsidies. Similar policies can also be found in other countries. Ethanol is a "first generation" biofuel (Zinoviev et al. 2007) which uses corn (or sugarcane in Brazil) as a feedstock and this corn use competes directly with grain production for food demand.

The direct competition has consequences. Crop prices increase worldwide and this can exacerbate food insecurity problems in developing countries. On the environmental side, the potential climate change mitigation benefits are argued to be compromised because of leakage effects (Murray et al. 2007, Searchinger et al. 2008, Fargione et al. 2008). Leakage happens when higher crop prices encourage other regions to increase production through intensification or deforestation both of which are associated with more greenhouse gas emissions. Moreover, leakage is international in nature owing to international trade.

As deforestation contributes approximately 17% greenhouse gas emissions annually (IPCC 2007), leakage in the form of indirect land use change (ILUC) is subject to careful investigations in the academic community (Fargione, et al. 2008, Searchinger, et al. 2008). Assessment of ILUC and leakage is possible only when both the international effect of one country's policy including any land use change plus adjustments in the country can be captured in the model. Existing assessments vary widely because of different modeling methods and assumptions employed (see discussion in Keeney and Hertel (2009), and Schneider and McCarl (2006)). One of the major tradeoffs in these models is geographical coverage versus the level of details in technologies, market structure and so on. This yields widely variable leakage estimates.

Our modeling exercise makes contribution to the leakage estimate by developing a global model with a detailed US component. We integrate the US Forest and Agricultural Sector Optimization Model (FASOM) and the Global Biomass Optimization Model (GLOBIOM), resulting in a model that is capable of carrying out a comprehensive assessment of the international effects of US agricultural policies.

Rather than answering a specific research question, this essay documents modifications undertaken to establish the integrated FASOM-GLOBIOM model. In the following sections, we will first describe the scope of the integrated model. We then describe the underlying economic principles and adjustments made to achieve the integration followed by discussion of the model's aggregation and calibration. Finally, we provide overview of the model equations and variables.

2. Conceptual Scope of the Integrated FASOM-GLOBIOM Model

The integrated FASOM-GLOBIOM model is a multi-period, recursive dynamic, price endogenous mathematical programming model depicting resource allocations of the agricultural and forestry sector of the world. The model portrays market equilibrium for each of the period on a 10-year time step basis. Key endogenous variables include:

- Commodity and factor prices,
- Production, consumption, export and import quantities,
- Land use decisions between and within sectors,
- Management strategies,
- Resource use,
- Economic welfare measures, and
- Environmental impact indicators—emission associated with land use change and fertilizer use.

The conceptual structure of the integrated FASOM-GLOBIOM model (the FG model hereafter) is shown in figure 2.1.

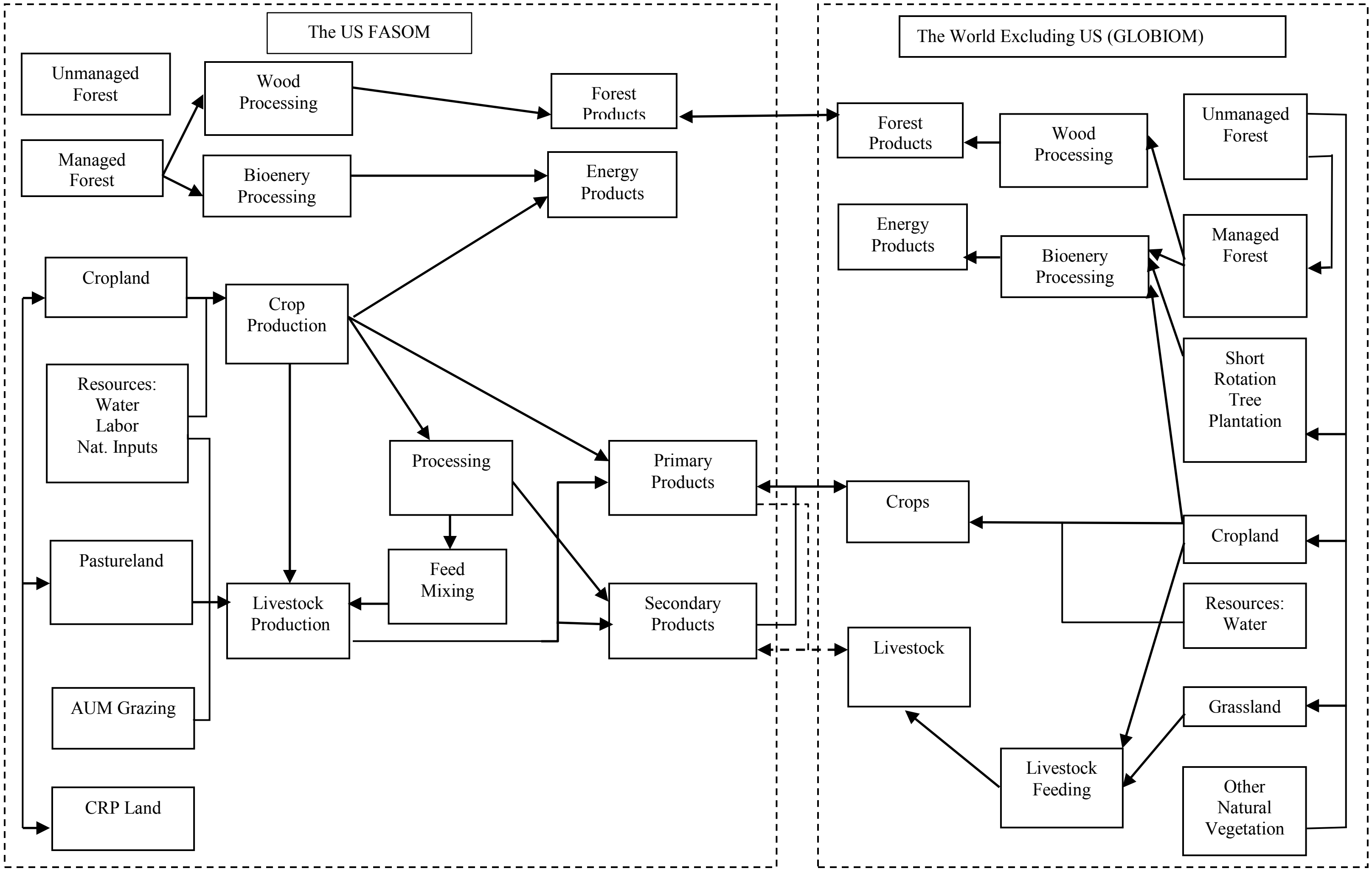

Figure 2.1: Conceptual Structure of the Integrated FASOM-GLOBIOM Model (Developed based on Havlik et al. (2010) and McCarl and Sands (2007))

2.1 Geographic Scope

In the FG model, the US is broken into the 11 market regions used in FASOM (table 2.1, adopted from (Adams et al. 2005)). For most of the commodities, production, livestock feeding and processing are modeled for 11 regions and demand is modeled on the national scale.

Table 2.1: US Region Definition

Key	Region	States/Subregions
CB	Corn Belt	All regions in Illinois, Indiana, Iowa, Missouri, Ohio
NP	Northern Plains	Kansas, Nebraska, North Dakota, South Dakota
LS	Lake States	Michigan, Minnesota, Wisconsin
NE	Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia
PNWE	Pacific Northwest-east side	Oregon and Washington, east of the Cascade mountain range
PNWW	Pacific Northwest-west side	Oregon and Washington, west of the Cascade mountain range
PSW	Pacific Southwest	All regions in California
RM	Rocky Mountains	Arizona, Colorado, Idaho, Montana, Eastern Oregon, Nevada, New Mexico, Utah, Eastern Washington, Wyoming
SC	South Central	Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Eastern Oklahoma, Tennessee, Eastern Texas (TxEast)
SE	Southeast	Virginia, North Carolina, South Carolina, Georgia, Florida
SW	Southwest	Western and Central Oklahoma, All of Texas but the Eastern Part -- Texas High Plains, Texas Rolling Plains, Texas Central Blacklands, Texas Edwards Plateau, Texas Coastal Bend, Texas South, TexasTrans Pecos

The rest of the world is broken into 27 regions, largely based on GLOBIOM which uses many of the same regions as FASOM (table 2.2). For most of the commodities, production is modeled based on land grids, which are defined by their geographical characteristics in the countries and demand is modeled on the regional scale.

Table 2.2: Rest of World Region Definition

	Region	Countries
1	ANZ	Australia, New Zealand
2	BrazilReg	Brazil
3	CanadaReg	Canada
4	ChinaReg	China
5	CongoBasin	Cameron, Central Africa, Congo Republic, Equator Guinea, Gabon
6	EU_Baltic	Estonia, Latvia, Lithuania
7	EU_CentralEast	Bulgaria, Czech, Hungary, Poland, Romania, Slovakia, Slovenia
8	EU_MidWest	Austria, Belgium, France, Germany, Luxemburg, Netherlands
9	EU_North	Denmark, Finland, Ireland, Sweden, United Kingdom
10	EU_South	Cyprus, Greece, Italy, Malta, Portugal, Spain
11	FormerUSSR	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova Republic, Russia, Tajikistan, Turkmen, Ukraine, Uzbekistan
12	IndiaReg	India
13	JapanReg	Japan
14	MexicoReg	Mexico
15	MidEastNorthAfr	Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, United Arab Emirates, Yeman
16	Pacific_Islands	American Samoa, Fiji Islands, French Polynesia, Kiribati, New Caledonia, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu
17	RCAM	Antigua Barbuda, Bahamas, Barbados, Belize, Bermuda, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guadeloupe, Guatemala, Haiti, Honduras, Jamaica, Martinique, Netherlands Antilles, Nicaragua, Panama, St. Kitts and Nevis, St. Lucia, St. Vincent, Trinidad and Tobago
18	RCEU	Albania, Bosnia and Herzegovina, Macedonia, Croatia, Serbia and Montenegro
19	ROWE	Andorra, Faeroes, Gibraltar, Greenland, Iceland, Isle of Man, Monaco, Norway, Switzerland, Liechtenstein
20	RSAM	Argentina, Bolivia, Chile, Colombia, Ecuador, French Guiana, Guyana, Paraguay, Peru, Surinam, Uruguay, Venezuela
21	RSAS	Bangladesh, Bhutan, Pakistan, Maldives, Sri Lanka, Nepal
22	RSEA_PAC	Vietnam, Cambodia, Korea (North), Laos, Mongolia
23	RSEA_OPA	Indonesia, Thailand, Myanmar, Brunei, Malaysia, Philippines, Singapore
24	SouthAfrReg	South Africa
25	SouthKorea	South Korea
26	SubSaharanAfr	Angola, Benin, Botswana, Burkina Faso, Burundi, Cape Verde, Chad, Comoros, Côte d'Ivoire, Djibouti, Eritrea, Ethiopia, Gambia, Ghana, Guinea, Guinea Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, São Tomé and Príncipe, Senegal, Seychelles, Sierra Leone, Somalia, St. Helene, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
27	TurkeyReg	Turkey

2.2 Input Scope

In FG there are several major inputs which involve land, labor and water. Each is discussed below.

2.2.1 Land Type

Land in each region is broken into two main categories, agricultural land and forest land. Agricultural land is further divided into four major types: cropland, grassland, plantation forest and other. Plantation forest refers to land for short rotation coppice (SRP), which is grown as energy crop and used for feedstock for the second generation biofuels. The type "other" is mostly marginal land or arable land in reserve. There are two types of forest land: primary forest and managed forest. Primary forest does not generate economic returns, but could be turned into productive land types, such as agricultural land or managed forest, although in some cases deforestation is involved.

The initial land acreage allocation is determined by the data in GLOBIOM for international cases and those in FASOM for the US. In turn, land use is determined by the relative net economic returns of competing activities. Land transfers have greenhouse gas emissions implications. Particularly when primary forests are cleared for cropland or grassland, substantial GHG emissions result, mainly in the form of lost carbon sequestration. In this way, the model can estimate carbon leakage in regions with large amount of primary forests, such as Brazil.

2.2.2 Non-land Inputs

Non-land inputs explicitly modeled in the FG model include fertilizer and water. Fertilizer use and irrigation choice (irrigation versus rain-fed) along with land allocation together determine yields and total production of the commodities. Associated with this modeling, we do environmental accounting on N, P and K run off and non-CO_2 GHG emissions and we are also able to investigate the internal value of water availability. Labor availability is also modeled in the US part of the model.

2.3 Commodity Scope

The FG model uses the commodity scopes of its component models. Seventeen major crops are simulated in GLOBIOM. Corn, soybean and wheat are the three most important crops in the US and these are the ones included in FASOM. Five species of wheat are included: soft white, hard red winter, soft red winter, durum and hard red spring. FASOM has five types of crop demand for the US: domestic demand, processing, livestock feed mixing, biofuel production and net export.[1] Processing and production of secondary commodities are included either to represent substitution or to depict demand for component products (Adams et al. 2005). The GLOBIOM model has four demand categories: domestic demand consisting of direct demand and demand for processing, livestock feed mixing, biofuel production and net exports. The integrated model has inherited the detailed modeling on the production side in the US, but the modeling in the GLOBIOM part is somewhat less detailed. As will be explained in detail in Section 3, the demand side, especially the US export demand and import supply components of international trade.

A comprehensive list of crops and livestock products modeled is presented in table 2.3.

[1] If net export is negative, i.e. import, then it could be regarded as supply.

Table 2.3: List of Crops and Livestock Products

27 Regions around the World Excluding US (Abbreviations)		US	
Crops			
Barley (BARL)		Corn	Oranges
Dry beans (BEAD)		Soybeans	Grapefruits
Cassava (CASS)		Soft white wheat	
Chickpeas (CHKP)		Hard red winter wheat	
Corn (CORN)		Soft red winter wheat	
Cotton (COTT)		Durum wheat	
Ground nuts (GNUT)		Hard red spring wheat	
Millet (MILL)		Cotton	
Potatoes (POTA)		Sorghum	
Rapeseed (RAPE)		Barley	
Rice (RICE)		Potato	
Soybeans (SOYA)		Rice	
Sorghum (SRGH)		Sugarcane	
Sugarcane (SUGC)		Oats	
Sunflower (SUNF)		Hay	
Sweet potatoes (SWPO)		Sugar beets	
Wheat(WHEA)		Canola (this is rapeseed)	
Livestock Products		***Primary Livestock Commodities***	
Buffalo		Non Fed Slaughter	Heifer Calves
Cattle		Feed Lot Beef Slaughter	Stocked Calves
Sheep		Calf Slaughter	Stocked Heifer Calves
Goats		Cull Beef Cow	Stocked Steer Calves
Shoat		Raw Milk	Dairy Calves
Pig		Cull Dairy Cow	Stocked Yearling
Poultry		Hogs for Slaughter	Stocked Heifer Yearling
		Feeder Pig	Stocked Steer Yearling
		Cull Sows	Horses and Mules
		Lamb Slaughter	Eggs
		Cull Ewes	Broilers
		Raw Wool	Turkeys
		Steer Calves	
		Secondary Livestock Commodities	
		Fed Beef	Evaporated Condensed Milk
		Non Fed Beef	Non Fat Dry Milk
		Pork	Butter
		Chicken	American Cheese
		Turkeys	Other Cheese
		Clean Wool	Cottage Cheese
		Fluid Milk	Ice Cream
		Skim Milk	Cream

There are two main outputs of the agricultural sector not included in table 2.3. Biofuel products included in the model include the first generation biofuel--crop ethanol and biodiesel-- and second generation biofuel—cellulosic ethanol. Modeling of the forest sector is completely based on GLOBIOM, which contains two types of forest land: primary forest and managed forest. Five types of products are produced from managed forest: saw logs, pulp logs, other industrial logs, pulp logs and biomass for energy.

3. Underlying Economic Principles and Achieving the Integration

In this section, we discuss the economic principles underlying the model and highlight features that make the integration possible.[2]

3.1 Competitive Behavior Simulation and Welfare Maximization

A mathematical representation of the FG model is presented in equations 2.1-2.5 (see notation in table 2.4). The model maximizes the sum of producer's profit and consumer surplus on a global basis (equation 2.1) in a recursive dynamic framework. This is essentially based on the First Fundamental Theorem of Welfare Economics (see detailed discussion in McCarl and Spreen (1980)). Its solution is a Pareto Optimal market equilibrium when the market is perfectly competitive, thus predicting equilibrium market prices and quantities.

There are four important sets of constraints, equations 2.2 - 2.5. The first constraints are a set of supply demand balance equations for various commodities (equation 2.2), forcing supply to be no less than demand. Second, a set of resource constraints and a set of technology constraints (equation 2.3 and 2.4) represent the feasible set of production. The recursive dynamics is introduced in equation 2.5. This

[2] Most of these features are implemented in file *intltradeconvert.gms* (if not indicated specifically) which will be called in the main file *41_model_structure.gms* that defines the model.

equation tracks the changes of land use over time—namely, the availability of one land type in period *t* equals the land in this category in the period (*t-1*) plus land coming into the category at period t minus land leaving the category. And notations of the equations are explained in table 2.4.

$$max\sum_{\gamma}\sum_{h}\int_{0}^{Q_{h\gamma}^{*}} P_{h\gamma}\left(Q_{h\gamma t}\right)dQ_{h\gamma t}-\sum_{\gamma}\sum_{-\gamma}\sum_{h}TC_{h,\gamma,-\gamma}NE_{h,\gamma,-\gamma,t}-\sum_{\beta}\sum_{i}\int_{0}^{X_{i\beta}^{*}} P\left(X_{i\beta t}\right)dX_{i\beta t}$$

[2.1]

$$s.t.\ \ Q_{h\gamma t}+\sum_{-\gamma}NE_{h,\gamma,-\gamma,t}-\sum_{\beta\in\gamma}\sum_{k}c_{h\beta k}Z_{\beta kt}\leq 0,\forall h,\gamma$$ [2.2]

$$\sum_{k}a_{i\beta k}Z_{\beta kt}-X_{i\beta t}\leq 0,\forall i,\beta$$

[2.3]

$$\sum_{k}b_{j\beta k}Z_{\beta kt}\leq Y_{j\beta t}\forall j,\beta$$

[2.4]

$$Y_{l,\beta,(t-1)}+\sum_{-l}LUC_{-l,l,t}-\sum_{-l}LUC_{l,-l,t}\leq Y_{l,\beta,t},\forall l$$

[2.5]

Table 2.4: Notation Used in Analytical Representation of the FG Model

Notation	Description
h	index for commodities (table 2.3)
β	the smaller production regions and land grids
γ	the 28 regions that aggregates the β 's and has an aggregated demand curve for every commodity
k	processing possibilities
i	purchased inputs
j	endowed inputs
l	a subset of j that denotes different land types
t	time period
$P_{h\gamma}\left(Q_{h\gamma t}\right)$	the inverse demand curve for commodity h in region γ
$P\left(X_{i\beta t}\right)$	the inverse supply curve for input i in region β
$TC_{h,\gamma,-\gamma}$	transport cost per unit of commodity h from region γ to region – γ
$NE_{h,\gamma,-\gamma,t}$	transportation (export) of commodity h from region γ to region – γ
$Q_{h\gamma t}$	total demand of commodity h of region γ at period t
$X_{i\beta t}$	purchased input i of region β at period t
$Y_{j\beta t}$	endowed input j of region β at period t
$Z_{\beta kt}$	the amount of production technology employed using process k by in region β at period t
$(c_{h\beta k}, a_{i\beta k}, b_{j\beta k})$	represents yield data associated with Z with $c_{h\beta k}$ being the yield parameter for output h and $a_{i\beta k}$ being the input use parameters of land and other endowed input and $b_{j\beta k}$ being it for purchased inputs

3.2 Assuring Product Consistency

The modeled regions interact with each other through trade flows. To link the GLOBIOM international model with the FASOM national US model, the first step is to deactivate the US part in the global model and then link the two models by equating their US incoming and outgoing trade variables. To establish the equality, the variables of the two component models need to be in consistent units; and consistent in what they are measuring. For example, the net export of soybeans of the US in the GLOBIOM model measures raw soybeans export from the US plus soybeans used in exported processed commodities (mainly soybean meal and soybean oil) while that in the FASOM model measures raw soybeans export from the US only. And therefore a procedure to further deal with this difference is needed.

Trade of eight crops between the US and rest of the world is explicitly modeled. These crops are corn, soybean, wheat, barley, potato, rice, sorghum and sugarcane. The differing commodity names are mapped through a tuple, and a unit conversion parameter (table 2.5) is included.[3] In turn, commodity price data are converted into a consistent base, and then transportation costs defined as price difference between regions are updated. [4]

[3] On the FASOM side, commodities not included in table 3.3 are modeled as what they used to be, that is their international trade is determined by a single excess supply/demand curve. On the GLOBIOM side, for those commodities that do not have counterparts in FASOM but do have small amount of import/export, these import/export are represented by a vertical demand/supply curve with quantity fixed at the GLOBIOM solution value.

[4] These steps are implemented in file *40_ModelUpdate.gms*.

Table 2.5: Unit Conversion of the Integrated Model

Crop in FASOM	Unit in FASOM	Crop in GLOBIOM	Unit in GLOBIOM	GLOBIOM units per unit in FASOM
Barley	Bushel	BARL	Tonne	45.930
Potatoes	CWT	POTA	Tonne	22.046
Soybeans	Bushel	SOYA	Tonne	36.744
Sorghum	CWT	SRGH	Tonne	22.046
Corn	Bushel	CORN	Tonne	31.495
Rice	CWT	RICE	Tonne	22.046
Soft White Wheat	Bushel	WHEA	Tonne	36.744
Hard Red Winter Wheat	Bushel	WHEA	Tonne	36.744
Durum Wheat	Bushel	WHEA	Tonne	36.744
Hard Red Spring Wheat	Bushel	WHEA	Tonne	36.744
Soft Red Winter Wheat	Bushel	WHEA	Tonne	36.744
Sugarcane	US tons	SUGC	Tonne	1.102

In addition to unit conversion, further modifications are made to insure consistency for two crops: soybeans and wheat.

So far, linkages are established only for crops not for livestock products, as the modeling of livestock is highly aggregated in the GLOBIOM component compared to that in the FASOM component. The US exports approximate 10% of its beef production annually and most of the trade happens between developed countries, which have slow economic growth and stable population. Therefore, we use a simple method to approximate this part of supply from the country. We solve the original GLOBIOM model and use the solution of livestock export of US as vertical excess supply curve to rest of the world.

- *Soybeans*

The majority of the world's soybeans are crushed and separated for oil and protein meal. This makes markets of the secondary commodities of soybeans as important as or even more important than the soybean market. The US crushes more than half of its soybean production, and exports 8.3 million metric tons of soybean meal and 1.3 metric ton of soybean oil in addition to 40 metric tons of raw soybeans each year in recent years. The export of soybean meal accounts for 23% of domestic production and 15% of the world market share and the shares for soybean oil are 14% and 13% respectively.[5] Together, they are equivalent to 495 million metric tons of soybeans—more than ten times the raw soybean exports of the country.[6]

Ideally, the model should reflect crushing technology possibilities plus the fact that demand for soybeans is determined in three different markets. However, neither model component includes complete global soybean meal and soybean oil data. We use a compromise method in which exports of primary commodities and processed commodities from the US are added together before they enter the international trade flow.

To forecast US exports of soybean meal and oil, we first use an extrapolation of historical data. Namely we find the best fit time trend for US soybean meal and soybean oil. In turn then in the model we force total soybean imports of the rest of the world to be equal the sum of the exports of raw soybeans plus the soybean equivalent amount of total soybean meal and oil exports of the US. We do not impose the transportation cost for the soybean meal and oil export; instead we add an ancillary restriction that for every US soybean buying trading partner that total soybean imports must be no less than the volume of raw soybean imports.

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[5] Data source: http://www.nass.usda.gov/QuickStats/Create_Federal_All.jsp and http://www.indexmundi.com/.
[6] Source of conversion rate: http://www.ussec.org/resources/conversions.html

- *Wheat*

FASOM models five different types of wheat corresponding to the more detailed classification of the crop while GLOBIOM models wheat as one crop. The production shares of the different types have been fairly stable and the price difference between the most expensive and the cheapest has been around 20% to 30% for more than 20 years[7]--this implies that they are close substitutes for some types of demand but not so for others.

The synchronization of wheat across the two models is done in three steps. First, we find the FASOM optimal type mix of wheat trade between US subregions and different regions of ROW[8] for the year 2000. Secondly, we calculate the national type mix of wheat production of US from historical data available on USDA. Finally, we add in restrictions that the production mix and the export mix of the US are in strict proportion to historical ones and assume that will hold for the entire modeling period.

3.3 Dynamic Adjustment

GLOBIOM is a recursive dynamic model with period length of 10 years, with results from one period feeding into the next one. FASOM is a multi-period fully dynamic model with period length of 5 years. The recursive dynamic method used in GLOBIOM is essentially assuming that the sector being modeled is in equilibrium within each of the periods and therefore does not allow forward looking behavior beyond the period length (McCarl and Spreen 1980). Due to the difference in dynamics, changes were required to make the two model components compatible.

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[7] Data source: http://www.nass.usda.gov/QuickStats/Create_Federal_All.jsp.
[8] A small amount of work on mapping the regions are required due to the difference in the region divisions of the two models.

3.3.1 Land Use Change

Land use change in the FG model is shown in figure 2.2. The arrows represent directions of land use change, namely land type at the tail of the arrow can be transferred into land type at the head of the arrow. Land types linked by double head arrow can be transferred into each other. The arrow with a dashed line represents land use change excluded in the model.

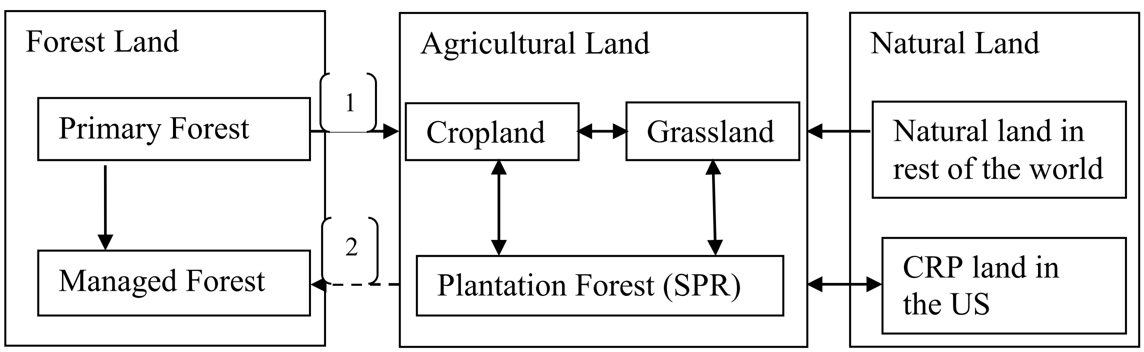

Figure 2.2: Land Use Change in the Integrated FG Model

The difference between recursive dynamics and full dynamics can be best demonstrated in the modeling of land use change. The optimal land use is determined by comparing the net present values of net return among all the possible uses. In the case of comparing the forest land and agricultural land, it involves comparing benefit flows that extend for several decades if the model were fully dynamic. However, in a recursive dynamic model like ours, what are being compared are benefit flows within the time interval of one simulation step. For example, the decision to clear primary forest for agricultural land, i.e. deforestation (represented by Arrow 1) in our model neglects the benefits generated by the forest beyond the simulation step. This neglect is valid here because (1) our simulation step is has a duration of 10 years and therefore short-run returns will still be captured; and (2) most primary forest clearance happens in developing countries in which the opportunities cost of holding land in forest is increasing over time and the long-run direct economic returns of primary forests is likely to be further neglected because of insecure tenure rights, especially at the local community level (Geist and Lambin 2002). Our modeling method precludes the modeling of afforestation (represented by Arrow 2).

Land enrolled in the Conservation Reserve Program (CRP) in the US is marginal land retired from production. Land owners receive payments from the government by enrolling their land in the program. Acreage of the CRP land in the model is based on the 2000 sign up. Contract length of the enrollment is 10 years, with possibility to extend. The time step of the integrated model is approximately the same as the contract length; therefore, enrollment in the CRP program is modeled as a static decision.

Variables $Y_{l,\beta,t}$ and $LUC_{-l,l,t}$ in equation 2.5 in Section 3.1 represents the recursive dynamics in the model correspond to availability of each land type and land use changes at each simulation period respectively.

4. Model Calibration

To aggregate and calibrate the FG model, crop mixes on a global scale are required to be a convex combination of historical crop mixes, a method proposed by McCarl (1982).

This method restricts the crop mix to the space spanned by a convex combination of historical crop mixes.

Then to further calibrate the model, the gap between the marginal cost of production and marginal revenue is closed using the method discussed in Fajardo et al.'s (1981) model of Nicaraguan agriculture. If perfect competition were assumed, farmers would produce to the point where marginal revenue (MR) equals marginal cost (MC). However, farmers may be constrained by information availability marketing and other factors affecting farmers that are not included in the model. Hence the MC revealed in the model may differ from the true one. Omitting the constraints will cause a gap between MR and MC. To close this gap, restrictions that force the observed land use, crop mix, livestock mix and forestry mix to be optimal solution of the model are imposed; in turn, the shadow prices of these restrictions could be regarded as the cost that is not taken into account (following a procedure like that used in the Howitt (1995)—Positive Mathematical Programming (the PMP method)). Later, these shadow prices are added into the crop production budgets as additional costs. [9] For more discussions on the aggregation and calibration methods, please refer to the paper written by Wiborg et al. (2005).

If international trade were dictated by the law of one price, we could have a good simulation of the real world up to this point. However, this is not the case. Trade flows are heavily affected by other factors, such as tariff and preference differences. Also

[9] This method is partly implemented in the data preparation and partly in equations **FORCE_LAND**, **FORCE_LUC**, **FORCE_LIVESTOCK**, **FORCE4, FORCE_FW** and **FORCE_ACAL_SUP** in file *42_caibration_1.gms.*

national food self-sufficiency goals play a role. As a consequence, actual productions of certain crops in specific regions are found to be higher than that revealed by the model solution and most of these crops are staple food of the region. In this case, import quotas were imposed so that a large proportion of domestic demand has to be met by domestic production. And the import quota is set at 120% of the observed for the period of 2000. The commodities and regions for which this was done are listed in table 2.6.

Table 2.6: Import Quotas Imposed in the FG Model

Crop	**Region**
Barley	EU_Baltic, EU_South, ROWE
Corn	EU_South, Sub-Saharan Africa
Rice	Japan, South Korea, Middle East and North Africa
Sorghum	Middle East and North Africa, Sub-Saharan Africa
Potato	Sub-Saharan Africa
Sugarcane	Sub-Saharan Africa

5. Data, Model Equations and Variables

As the integrated model is built on the FASOM model and GLOBIOM model, data description of the integrated model can be found in Adam et al. (2005) for the FASOM part and Havlik et al. (2010) for the GLOBIOM part. Overviews of equations and variables in the model are presented in table 2.7 and table 2.8 respectively.

Table 2.7: Overview of Equations of the FG Model

Equation Name	**Description**
AGCRPACREUP	Limits crop mix in the US and are explained in FASOM (Adams et al, 2005).
AGCRPMIXC	
AGCRPMIXCTRAN	
AGCRPMIXLO	
AGCRPMIXUP	
AGCRPREVERTCONVEX	Linearizes the reversion of CRP with increasing, convex costs in the US.
AGCRPREVERTEQ	Identity that calculates total CRP reversion in the US.
AGCRPREVERTLIM	Limits regional maximum CRP reversion in the US.
AGCRPREVERTNATLIM	Limits national maximum CRP reversion in the US.
AGGRAZINGUSEEQ	Calculates agricultural land for animal grazing in the US.
AGLIVESTOCKMIXNAT	Limits livestock mixes must be in the convex cone of historical data in the US.
AGMANUREMGT	Computes GHG emission related to manure management in the US.
AGMAXPASTURETOCROP	Limits maximum amount of reversion in the US.
AGPASTLANDEXCHANGE	The accounting equation of land transfer between pasture and cropland in the US. Refer to equation LUCDET_EQU for detailed explanation.
AGPROCESSMAXPURCHINPUT	Limits inputs available for processing in the US.
AGPROCESSMAXPURCHINPUTREL	
AGPROCESSMINPURCHINPUT	
AGPROCESSNATMAXPROD	Limits the production level of the processed commodities in the US.
AGPROCESSNATMINPROD	
AGPRODBAL	Commodity demand supply balance in the US.
AGRESBALANCE	Calculates water and labor use in the US.
AGRESCONVEX	Convexity equation for resource use in the US and refer to equation DEMAND_CONVEXITY for explanation of convexity equation.
AGRESIDENTITY	Sets total resource supply to that arising from the step variables in the US.
AGRESMAX	Limits the usage to be no more than maximum available in the US.
AGSDCONVEX	Convexity equation for commodity supply and demand in the US and refer to equation DEMAND_CONVEXITY for explanation of convexity equation.
AGSDIDENTITY	Sets total commodity demand and supply to that arising from the step variables in the US.
BASE_BIOEN_DEMAND1	Impose estimated base bioenergy production.
BASE_BIOEN_DEMAND2	
COFIRESTEPALLPROCESS	Impose co-fire limits in the US.

Table 2.7_Continued: Overview of Equations of the FG Model

Equation Name	**Description**
COFIRESTEPREGPROCESS	Impose co-fire limits in the US.
COPRFEEDMAX_EQU	Limits biofuel co-product use for feeding use if appropriate.
CROP_SHARE_MAX	Limits crop mixes must be in the convex cone of historical data.
CROPLAND_EQU	Limits total cropland no greater than its availability.
CROPLANDUSE_EQU	Limits shares of crop land of different management practices.
DEFOR_CONTROL	Control whether, where and how much deforestation is allowed.
DEFORLOGS_EQU	Calculates logs from deforestation.
DEMAND_CONVEXITY	A convexity equation that is used in representing the area under the demand curves in a linear fashion allowing the problem to be solved as a linear program for time reasons. This uses separable programming as explained in Baumes and McCarl.
DEMAND_IDENTITY	An identity equation sums over all the steps and obtains total demand.
DS_BALANCE	Commodity demand supply balance.
EQU_CALI_EXPORT1	Impose import and export quotas.
EQU_CALI_EXPORT2	
EQU_CALI_IMPORT1	
EQU_CALI_IMPORT2	
EQU_CALI_PRODUCTIONA	Computes deviation of land allocation from that observed.
EQU_CORNEXPSTEP1	Separable programming for US corn export.
EQU_CORNEXPSTEP2	
EQU_FEEDUP	Impose upper bound of feed use.
EXG_FOOD_DEMAND1	Imposes food requirements on crops.
EXG_FOOD_DEMAND2	Imposes food requirements on meat.
EXG_FOOD_DEMAND3	Imposes food requirements on calories.
EXG_WOOD_DEMAND	Imposes wood product demand requirements
EXPCONVERT	Unit conversion of different trade variables.
EXPCONVERT1	An identity equation sums over all the steps and obtains total export.
FEED_BALANCE	Deals with feeding of livestock.
FEED_BALANCEILRI	
FEED_BALANCELOC	
FORCED_SOLU_EXP	Fix US export/import modeled in GLOBIOM but not in FASOM.
FORCED_SOLU_IMP	
FORCEREGPROCESS	Limits the production level of the processed commodities in the US.

Table 2.7_Continued: Overview of Equations of the FG Model

Equation Name	**Description**
GRAS_BALANCE	Deals with feeding of livestock.
GRASLAND_EQU	Limits total grassland no greater than its availability.
HARVLAND_EQU	Limits total managed forest no greater than its availability.
IMPCONVERT	Unit conversion of different trade variables.
INTCROPMIXEQULO	Limits crop mixes in 27 regions excluding US.
INTCROPMIXEQUUP	
LUCDET_CONVEXITY	Convexity equation for land use change in 27 regions excluding US and refer to equation DEMAND_CONVEXITY for explanation of convexity equation.
LUCDET_EQU	The accounting equation for land use change; namely, $\mathrm{Area}_{\mathrm{type}} + \mathrm{LandTransferLeaving}_{\mathrm{type}} - \mathrm{LandTransferCoimgin}_{\mathrm{type}} - \mathrm{BaseArear}_{\mathrm{type}} \leq 0, \forall \mathrm{type}$ and $\mathrm{BaseArear}_{\mathrm{type}}$ is updated each solve by $\mathrm{BaseArear}_{\mathrm{type}} = \mathrm{Area}_{\mathrm{type}}$.
LUCDET_IDENTITY	An identity equation sums over all the steps and obtains total land use change.
MAXSAWLOG_EQU	Limits harvested logs.
MAXTHWLOG_EQU	
MAXTSWLOG_EQU	
MINLIVESTOCK_EQU	Deals with feeding of livestock.
NOTRADEUSREGIONA	Fix US export/import modeled in FASOM but not in GLOBIOM.
NOTRADEUSREGIONB	
NOTRADEUSREGIONC	
NOTRADEUSREGIOND	
OBJECTIVE_EQU	Computes the sum of the agricultural consumer's plus producer's surplus across all of the model regions. This consists of the area under the product demand curves minus the area under the explicit input supply curves. Production cost, processing cost and transportation cost are also subtracted.
OBLIG4PRD_EQU	Forces minimum levels of production of forest products not represented in the objective function.
POLES_ENGSCEN_EQU	Bioenergy production as defined in POLES scenarios.
RESOURCE_CONVEXITY	Convexity equation for resource use and refer to equation DEMAND_CONVEXITY for explanation of convexity equation.
RESOURCE_IDENTITY	Sets total resource supply to that arising from the step variables.
SOYBEANADJ1	Aggregates exports of raw soybeans, soybean meal and soybeans oil of US, see explanation in Section 3.2.

Table 2.7_Continued: Overview of Equations of the FG Model

Equation Name	Description
SOYBEANADJ2	Aggregates exports of raw soybeans, soybean meal and soybeans oil of US, see explanation in Section 3.2.
SOYBEANADJ3	Projects US exports of soybean meal and soybean oil.
SRPLAND_EQU	Limits total land for short rotation coppice no greater than its availability.
SRPSUIT_EQU	Limits short rotation coppice land to be no greater than total land suitable for its plantation.
STOVER_BALANCE	Deals with feeding of livestock.
SUBSFARMING_EQU	Fixes the amount of subsistence farming to be equal to that observed.
TRADECOST_CONVEXITY	Convexity equation for net export and refer to equation DEMAND_CONVEXITY for explanation of convexity equation.
TRADECOST_IDENTITY	Sets total net export to that arising from the step variables.
WATER_ACCOUNT	Calculates and limits water usage.
WELFAR_USFASOM	Similar to OBJECTIVE_EQU, but only computes the surpluses in the US.
WHEATADJ	Forces wheat to be the major feedstock of bioenergy in the former USSR region.
WHEATRATIO	Forces US wheat export follows specific species mix, see explanation in Section 3.2.
WHEATRATIO_PRODUCTION	Forces US wheat production follows specific species mix, see explanation in Section 3.2.

Table 2.8: Overview of Variables of the FG Model

Variable Name	Description
AGCROPBUDGET	Variable calculates crop budgets in the US.
AGCRPMIX	Variable for crop mix by irrigation type in the US.
AGCRPREVERT	Variable calculates CRP reversion in the US.
AGCRPREVERTS	Variable for linearization of CRP reversion in the US.
AGDEMAND	Variable calculates commodity demand in the US.
AGDEMANDS	Variable for linearization of commodity demand in the US.
AGDEMARTIF	Artificial production to meet demand.
AGIDLELANDPASTURE	Variable calculates idle land pasture in the US.
AGLIVEMIX	Variable for livestock mix in the US.
AGLVSTBUDGETNSPR	Variable calculates livestock budgets in the US.
AGLVSTMANURE	Variable for improved manure use in the US.
AGMIXR	Variable for crop mix in the US.
AGMIXR_AUG	Variable allows for augmented crop mix in the US.

Table 2.8_Continued: Overview of Variables of the FG Model

Variable Name	**Description**
AGPASTLNDUSECHG	Variable calculates agricultural land use change in the US.
AGPROCESS	Variable calculates processing budgets in the US.
AGREGPROCESS	Variable calculates regional processing budgets in the US.
AGREGPROCESSPEN	Variable calculates regional process cofire penetration budgets in the US.
AGRESSEPSUPPLY	Variable for linearization of regional non-land resource supply in the US.
AGRESSUPPLY	Variable calculates regional non-land resource supply in the US.
AGSUPPLY	Variable for commodity import of the US.
AGSUPPLYS	Variable for linearization of commodity import of the US.
AGTRADE	Variable calculates international trade.
AGTRADE_EXP	Variable calculates US commodity export.
AGTRADE_EXPS	Variable for linearization of US commodity export.
AGTRADE_IMP	Variable calculates US commodity import.
AGTRANSPRIM	Variable calculates commodity transfer between regions and the nation in the US.
AGUSEGRAZING	Variable calculates grazing resource use in the US.
ART_VAR	Artificial variables.
ARTAGCRPMIXLO	Artificial variables to meet mix minimum.
ARTAGLIVESTOCKMIXNAT	Artificial for national mix.
ARTAGPROCESSMAXPURCHINPUT	Artificial for forced biofuel processing.
ARTAGPROCESSMINPROD	Artificial for forced biofuel processing.
ARTFORCEREGPROCESS	Artificial for force in regional processes.
ARTREGDEVELOPMENTFOR	Artificial regional development.
ARTRELIEVEAGGRAZINGUSEEQ	Artificial grazing
CROP_VAR	Variable calculates acreage of crops.
CSPS	Sum of consumer surplus and producer surplus of the world.
DEMAND_STEP	Variable for linearization of commodity demand.
DQUANTITY	Variable calculates commodity demand.
FEEDQUANTITY	Variable calculates feed quantity.
GRAS_VAR	Variable calculates acreage of grassland.
HARVEST_VAR	Variable calculates acreage of harvested forest.
INTCROPMIXVAR	Variable for crop mix in 27 regions excluding US.
LANDAVAIL_VAR	Variable tracks land availability of all types.
LIVE_VAR	Variable calculates livestock production.
LUCDET_STEP	Variable for linearization of land use change.

Table 2.8_Continued: Overview of Variables of the FG Model

Variable Name	**Description**
LUCDET_VAR	Variable calculates land use change.
PQUANTITY	Variable calculates supply of processed commodities.
RESOURCE_STEP	Variable for linearization of non-land resource use.
RESOURCE_VAR	Variable calculates non-land resource use.
SHIPMENTS	Variable for international trade.
SPR_VAR	Variable calculates acreage of short rotation coppice.
SQUANTITY	Variable calculates supply of composite livestock products.
SQUANTITY_DEFOR	Variable calculates quantity of biomass produced from primary forest clearance.
SQUANTITY_FOREST	Variable calculates quantity of biomass produced in harvested forest.
TOLAGLIVESTOCKMIXNAT	Slop in mix constraint
TRADECOST_STEP	Variable for linearization of international trade.
VAR_CALI_PRODUCTIONNE	Variable for examination of land allocation deviation from that observe red.
VAR_CALI_PRODUCTIONPO	Variable for examination of land allocation deviation from that observe red.
WELFARE_USFASOM	Sum of consumer surplus and producer surplus of US.

6. Basic Results and Sensitivity Analysis

We present the model solutions and actual values of productions and acreages of the US and rest of the world, and US export of corn and soybean in table 2.9. In the base period, model solutions on US corn and soybean production, soybean production in rest of the world and crop acreages are close to observed. But corn production in rest of the world is 13% higher and solution on US export does not replicate the observed very well either. In the one period ahead simulation, corn production predict in rest of the world is very close to the actual average of 2005-2009 but on a smaller acreage base. The model under predicts US corn export, US soybean export and soybean production in rest of the world.

This implies that parameters of demand growth rates in the model are very possibly smaller than the actual ones.

Table 2.9: Comparing Model Results with Actual

		Base Period 2000				Simulation of 2010		
Solution on	Region	Model Prediction	Actual Average of 1995-2004	Ratio of Prediction to Actual		Model Prediction	Actual Average of 2005-2009	Ratio of Prediction to Actual
Corn production	US (in Thousand Bushel)	9489899	9530603	1.00		12878356	11976579	1.08
	Rest of the world (in Thousand Metric Tonne)	409837	361591	1.13		469674	472186	0.99
Corn Acreage	US (in Thousand Acre)	67209	71228	0.94		70126	78771	0.89
	Rest of the world (in Thousand Hectare)	105020	110438	0.95		115728	125023	0.93
Corn Export	US (in Thousand Bushel)	1521323	1883789	0.81		1376458	2044939	0.67
Soybean Production	US (in Thousand Bushel)	2775940	2662032	1.04		2831626	3053641	0.93
	Rest of the world (in Thousand Metric Tonne)	100695	97013	1.04		106437	149373	0.71
Soybean Acreage	US (in Thousand Acre)	66072	70194	0.94		55338	72419	0.76
	Rest of the world (in Thousand Hectare)	47667	46944	1.02		58051	66534	0.87
Soybean Export	US (in Thousand Bushel)	1032833	940856	1.10		673600	1149688	0.59

As a very preliminary test of the robustness of the model, we randomly draw a non-zero parameter at a time and impose positive and negative 1% shocks to the value of the parameter and re-solve the model. And we repeat this procedure for several times. Table 2.10 presents solutions of production, acreage and US export of corn and soybean with shocks to five parameters relative to the base predictions. Overall, solutions on export are more sensitive to parameter shocks than production and acreage. Production and acreage of soybean are more volatile with the shocks than that of corn, and changes of the latter are within 1%.

Table 2.10: Selected Solutions with Parameter Shocks Relative to the Base Predictions (Note: "ROW" stands for "rest of the world")

		Ratio to Baseline Predictions									
		Corn					Soybean				
		Acreage _ROW	Acreage _US	Export _US	Production _ROW	Production _US	Acreage _ROW	Acreage _US	Export _US	Production _ROW	Production _US
CROP _DATA1	Shock_ low	1.01	1.00	1.03	1.00	1.00	1.00	1.00	1.06	0.98	1.00
	Shock_ up	1.01	1.00	1.03	1.00	1.00	1.00	1.00	1.06	0.98	1.00
CROP BUD1	Shock_ low	1.01	1.00	1.03	1.00	1.00	1.00	1.00	1.06	0.98	1.00
	Shock_ up	1.01	1.00	1.03	1.00	1.00	1.00	1.00	1.06	0.98	1.00
CROP BUD2	Shock_ low	1.01	1.00	1.03	1.00	1.00	1.00	1.00	1.06	0.98	1.00
	Shock_ up	1.01	1.00	1.03	1.00	1.00	1.00	1.00	1.06	0.98	1.00
PROC BUD1	Shock_ low	1.02	1.00	1.03	1.00	1.00	1.00	1.00	1.06	0.98	1.00
	Shock_ up	1.00	1.00	1.03	1.00	1.00	1.01	1.00	1.06	0.98	1.00
PROC BUD2	Shock_ low	1.01	1.00	1.03	1.00	1.00	1.00	1.00	1.06	0.98	1.00
	Shock_ up	1.01	1.00	1.03	1.00	1.00	1.00	1.00	1.06	0.98	1.00

7. Limitations

There are two major limitations in this model. First, due to the lack of data availability, the soybean-based commodities (raw soybeans, soybean meal and soybean oil) are presented in a compromised way. This could have considerable impacts on the leakage assessment, as land use change in South America, in which a large part of arable land is located, is sensitive to changes in these markets.

Second, that demand growth parameters tend to be smaller than the actual exemplifies the uncertainties in our assessment. The leakage effect tends to be under-estimated, provided that land with high productivity is converted sooner than lower ones.

CHAPTER III

CROP YIELD GROWTH AND ITS IMPLICATION FOR THE INTERNATIONAL EFFECTS OF US BIOENERGY AND CLIMATE POLICIES

1. Introduction

In recent years, society has been placing greater demands on the agricultural sector making it , in addition to its traditional food and fiber roles, also a source of bioenergy and a possible source of greenhouse gas mitigation(see IPCC (2007)). As a consequence, on the bioenergy side, US corn usage for ethanol has risen from 15.9 million tons (below 5% of the total crop) to 104 million tons (almost 40%) between 2001 and 2010.[10] The consequences of this demand expansion are multi-faceted. In the market, the bioenergy expansion coupled with other forces have caused crop prices to increase substantially (Trostle 2008, Abbott, Hurt and Tyner 2009), in turn causing food insecurity problems in developing countries (FAO 2008). Stimulated by higher prices, corn production in the US has expanded by 40% in the past decade both due to changes in the extensive margin (e.g., expansion of cropland via clearing of grassland, unprotected forest) and the intensive margin (e.g. using improved seeds to increase yield) (Melillo, et al. 2009) with 11% more corn acreage. Beyond the market, such developments will inevitably have environmental consequences, notably increasing greenhouse gas emissions and chemical

[10] Data source: Earth Policy Institute (http://www.earth-policy.org/).

use/runoff plus erosion. In the realm of climate change mitigation, the price effects stimulate what is called the problem of leakage (Murray, et al. 2004) which happens when mitigation policies reduce net GHG emissions in one context but increase prices that in turn causes production expansion and associated emissions increases elsewhere. In addition to increased GHG emissions, there might be other environmental consequences on the local or regional scale, such as pollution to watersheds or loss of biodiversity, depending on the form of leakage.

Baker et al. (2010) found that rising prices would have modestly positive welfare consequences in the US, as benefits to producers outweigh the loss to consumers. However, this may not be true if the scope is broadened from a US centric national agricultural sector, to a global analysis that also considers environmental damages. Additionally the price increases may cause substantial welfare losses for some people in the developing world. Assessments on the international scale are often found in reports of international organizations, such as the FAO.

A global issue is the conceivably negative environmental consequences associated with the expansion of crop production, particularly in the form of leakage in the form of indirect land use change (ILUC). Searchinger, et al. (2008) argues that large carbon leakage causing an overall net emissions increase can arise through ILUC. However, there are some uncertainties clouding the magnitude of the consequences. EPA (2010) finds that the GHG implications are far lower than asserted by Searchinger. Also a number of studies suggest that alternative assumptions regarding values on key parameters (such as crop yield, bilateral trade responses), model assumptions (such as geographical scope) and assumed leakage responses as to whether new lands come from forest or grasslands can lead to diverse estimations in policy assessments (Keeney and Hertel 2009, Schneider and McCarl 2006, EPA 2010). For example, Searchinger et al. (2008) argues that promoting use of bioenergy will lead to large amount of deforestation and associated carbon emissions that would not have happened without the policy creating an initial carbon debt and that the offset benefits can only be realized in the far future. In contrast, their finding is criticized for neglecting the price response of crop yield growth-- by using the low range of elasticity found in early literature, Keeney and Hertel (2009) indicates that 30% of the marginal ethanol demand in an initial 5 year term can be met by yield gains, which is 10% higher than the "best case" used in the Searchinger et al. (2008), implying the acreage expansion would be less than asserted by the latter. Fundamentally, these two studies differ in their assumptions regarding how supply, the product of acreage and yield, catches up with growing demand. As there is an ultimate limit on acreage, it is worth investigating the role of yield and prospects for yield growth.

Recent discussions on reductions in crop yield growth are seen both in the economics literature (Alston, et al. 2009, Villavicencio 2010) and in other fields, such as biology (Arizen, et al. 2008). Studies of the crop yield growth have a variety of motivations, including whether climate or environmental change has exerted negative effects and whether changes in societal investment patterns have had an unfavorable result. Alston et al. (2009) investigates productivity growth of the agricultural sector instead of crop yield growth and finds that the productivity growth has slowed down in the past two decades. Arizen et al. (2008) regresses crop yield growths on time with a linear function and concludes that there is no evidence that crop yield growths have slowed down. Whether this is happening is actually difficult to determine. In particular, such a trend in the data may be found not only because a slowdown in yield growth was occurring but also because of different measurement approaches (absolute growth vs. relative growth); time frames and functional form/estimation technique.

If one is to estimate the determinants of crop yield using a production function result, then many independent variables would be included, notably climate conditions, soil type/characteristics, varieties and input use. If this were extended dynamically, then research and extension expenditures would be included. In this chapter, rather than taking a production function approach, we examine the more aggregate characteristics of crop yield growth with time series techniques. We will do this using US data. Specifically, we consider both exponential growth and linear growth possibilities in the crop yield growth trend with a possible change in the past 70 years. Subsequently we will use the results in the form of alternative yield growth scenarios up to the year 2030 to investigate the international effects of U.S. bioenergy policies on market prices, exports, production, land use and welfare. The study will utilize the global agricultural sectoral model discussed in the previous chapter.

Uncertainty is inherent in leakage assessment, which is essentially the difference in predictions for the future land use under different policy scenarios. Assumptions on the values of crop yield growth rates are one of the key factors in these predictions. The contribution on this paper come in two regards: 1) a more reliable estimate on crop yield growth rates is offered; and, 2) the relationship between environmental consequences of bioenergy/climate policies and crop yield is explicitly explored.

2. Examination of Historical Crop Yield Growth Trend of US

This study focuses on 8 major field crops at the national level in the US: corn, soybean, wheat, cotton, sorghum, oats, barley and hay. Their yield data for the years 1940-2009 are collected from the Quick Stats data set developed by the National Agricultural Statistics Service of US Department of Agriculture. The data are plotted in figure 3.1.

Now we turn our attention to estimating the yield growth rate permitting potential changes in yield growth rates over time. To do this we examine the historical yield growth rate in a two-step process: 1) we detrend the data to obtain residuals; 2) we examine the residuals to see if they are stationary[11] and/or if they exhibit correlation across time.

[11] Time series data $\{X_t\}$ is strictly stationary if $(X_1,\ldots,X_n)$ and $(X_{1+h},\ldots X_{n+h})$ have identical joint distribution for all integers h and $n \geq 1$. Time series analysis typically works with weaker assumption that says the two random vectors have the same first and second moments, i.e. their mean and covariance (Brockwell and Davis 2002).

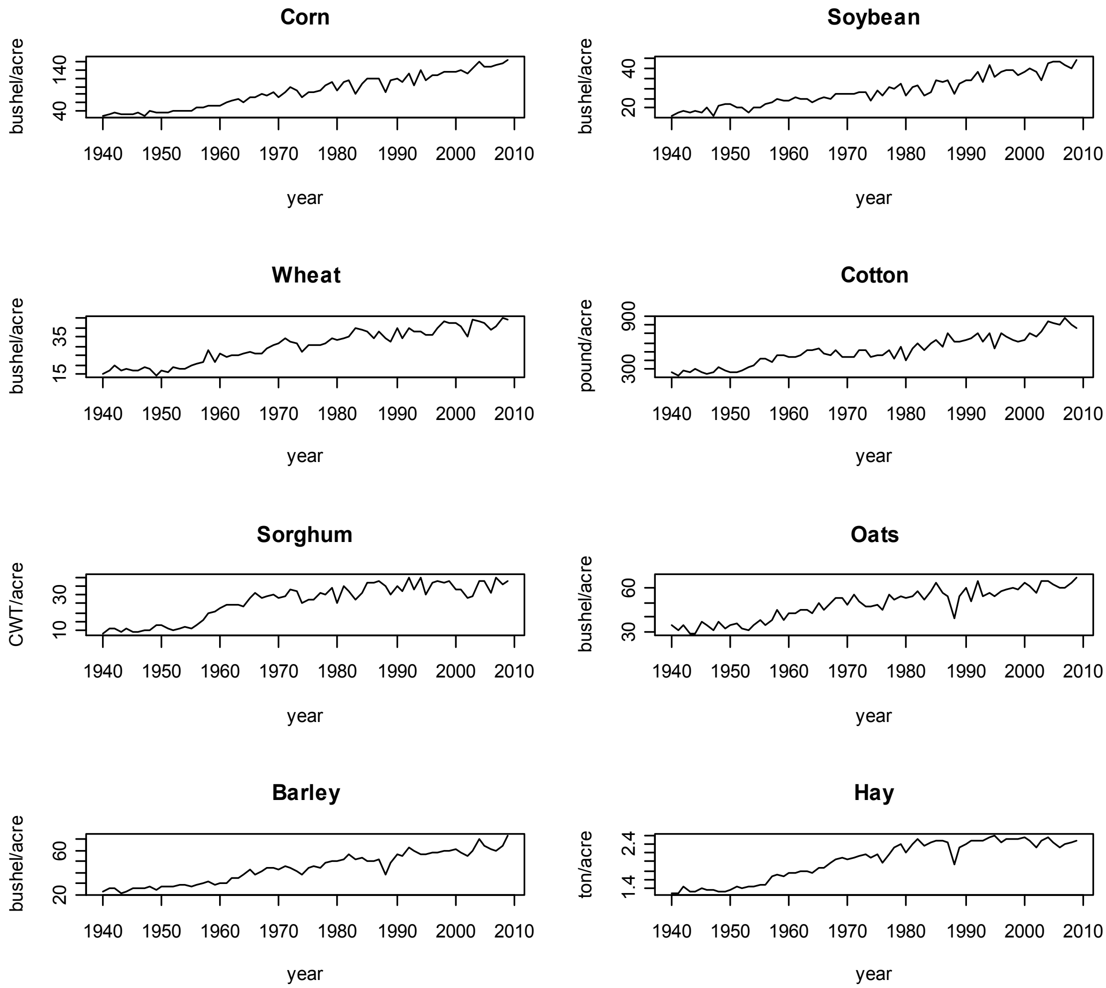

Figure 3.1: National Average Yields Per Acre for 8 US Major Crops (1940-2009). Source: http://www.nass.usda.gov/QuickStats/Create_Federal_All.jsp.

There are two ways of detrending the data: 1) a parametric way, such as finding the trend and/or seasonality function; and 2) a non-parametric way, such as differencing (the so-called Box-Jenkins method) until the resultant data is stationary (Brockwell and

Davis 2002). We follow the classical way to fit crop yield data with a time trend, which allows for greater flexibility in choosing time trend functions.[12]

The regression functions we consider use yield and/or its logarithm as the dependent variable with a linear time-independent variable corresponding to linear and exponential growth processes respectively.[13] In view of the concern of crop yield growth reducing over time, we also allow for a possible break in the trend function and consider all the possible combinations of the trend functions before and after the break, namely exponential trend followed by exponential trend, exponential trend followed by linear trend, linear trend followed by linear trend, and linear trend followed by exponential trend.

The best fit trend function is determined by the method of hold-out validation.[14] The procedure will be presented in detail in Section 2.1. After the best yield growth rate function is found, correlation of residuals will be checked to see whether further modeling is needed.

Following the time trend estimation, we then test whether the growth rate estimations of the two time segments are statistically different. The structural break test

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[12] If the differencing procedure were used, it would impose implicit assumptions on the growth process. Differencing in original data implies an assumption of linear growth while differencing in logarithm of the original data assumes exponential growth. If the process grows in a mixed way, the derived data will not be stationary, which might jeopardize the following analysis.

[13] For linear trend, *yield=a+b*year*, implying an ever decreasing growth rate, that is, $GrowthRate = \frac{a + b * Year}{a + b * (Year - 1)} - 1 = \frac{b}{a + b * (Year - 1)}$ and $\frac{\partial GrowthRate}{\partial Year} = -\frac{b^2}{(a + b * (Year - 1))^2} < 0$. For exponential trend, $yield = e^{a_1 + b_1 * Year}$ implying $GrowthRate = \frac{e^{a_1 + b_1 * Year}}{e^{a_1 + b_1 * (Year - 1)}} - 1 = e^{b_1} - 1$, which is constant over time.

We have also tried a quadratic time trend; however, our result indicates that the results are highly sensitive to the specific data set used-- even though it sometimes provides good estimates of the trend, it performs poor in validation.

[14] http://research.cs.tamu.edu/prism/lectures/iss/iss_l13.pdf

employed here contains a large number of competing specific tests which can be classified fundamentally by whether the test assumes the break date is known or not. When the break date is assumed to be known, the classical Chow test can be applied. When the break date is assumed to be unknown, the tests typically have higher critical value leading to the null hypothesis that there is no difference in the estimated parameter values (or in other words, there is no structural break) being rejected less frequently (Hansen 2001). However, investigators typically have some a priori but not complete knowledge regarding the occurrence of the change and there is no clear cut answer to the question whether to assume the break date is known or unknown (Hansen 2001, Maddala and Kim 1998). In fact, research like ours is motivated by observations that technical progress has slowed down (e.g. Alston et al. (2009)) but we do not exactly know when the change occurred. Identification of the break point in our case will be data driven. Therefore, we will use both types of tests.

2.1 Estimating Yield Growth Trends for US Crops

Let us begin with corn, the most prevalent crop in US agriculture. The left panel of figure 3.2 shows the average corn yield in the United States from 1940-2009, with a fitted linear model passed through it where $y=a+b*year$, with a=-3681 and b=1.91. The estimated slope on the year variable suggests the yield is growing at 1.91 bushels/year, equivalent to a 6.57% increase in 1940 but only 1.15% in 2009 where the yields in those periods average 28.9 bushels and 164.7 bushels respectively.

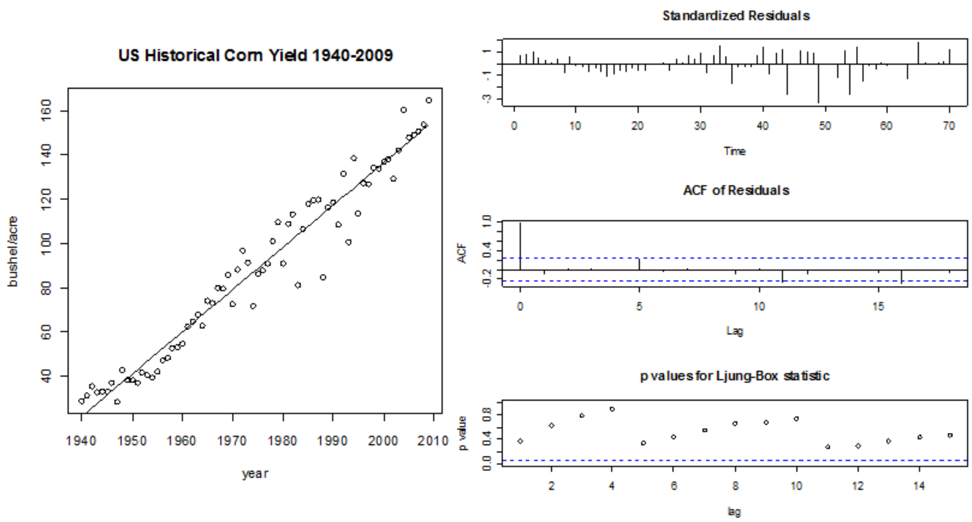

Figure 3.2: US Historical Corn Yield 1940-2009 with Fitted Linear Model

After the regression, we need to determine whether there is additional information in the data. A way to do this is to test whether the autocorrelations of residuals are different than zero. Zero autocorrelations of residuals suggest it is very likely that the deterministic part of the data has been fully captured. Specifically, Ljung-Box test is used, which is defined as $Q = T(T+2)\sum_{k=1}^{s}\frac{r_k^2}{T-k}$ .The null hypothesis of the test is that the data is random. Applying the test to the residuals of the linear regression of corn data, the null hypothesis cannot be rejected.

However, the residual plot of the fitted linear model (figure 3.2) shows some factors to take into consideration. Firstly, residuals of the model are spreading out showing that variance is increasing with time, which is no surprise since the average US yield has increased by around 3 fold over the whole period. More importantly, the standardized residual plot (the first panel on the right) does not seem to be random, especially for the first three decades. Fitted values of the model tend to persistently underestimate the yield data for the first 10 years and overestimate the next 10. Then the residuals become and remain positive for another decade with only 1 or 2 exceptions. Since this pattern occurs only in a segment of the data and does not recur, the Ljung-Box test, when applied to the residual of the whole period, may not have the power to reject the null. This pattern suggests nonlinear yield growth. Careful examination of figure 3.2 seems to indicate that the yield grew at a different rate up until about 1970 than it did after that. This can be seen better when the logarithm of corn yields are plotted against year (figure 3.3). [15]

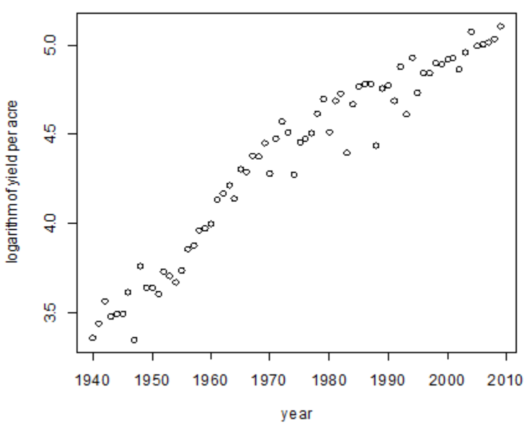

Figure 3.3: Logarithm of Corn Yield of US 1940-2009

[15] Another way to test for nonlinearity growth is to do a Box-Cox transformation on the yield, then regress the transformed data on time, namely, $B(y_t,\lambda)=a+bt+\varepsilon_t$, where $B(y_t)$ denotes the Box-Cox transformation: $B(y_t,\lambda)=\begin{cases}\dfrac{y_t^{\lambda}-1}{\lambda}, \lambda \neq 0\\ log(y_t), \lambda = 0\end{cases}$ (Davidson and MacKinnon 1993). Here, Box-Cox transformation is used as a robustness check in the deciding whether the data can be adequately modeled with a simple linear or exponential model.

In the case of corn, the estimation gives $\lambda=0.7086$ and both *0* and *1*, which correspond to exponential growth and linear growth respectively, are outside of the 95%confidence interval of the estimated λ. This indicates that the data cannot be adequately modeled with either a simple linear model or a simple exponential model. Results on other crops will be discussed below at relevant point..

Consequently, we adopted an estimation procedure that fit two functions of potentially different forms (exponential and linear) with a break point where the estimation can change parameters. There are two parameters in the time trend function: the intercept and the slope. The models are called unrestricted when both coefficients are allowed to change-- these models will have the most freedom to fit data but are very likely to have jumps at the breakpoint between the two fitted regressions. The models in which the segments must connect at the breakpoint with each other are called restricted models. The restriction costs one degree of freedom in choosing parameters, i.e. only the slope coefficient can change freely. In other words, the restricted versus unrestricted refers to whether the absolute level of crop yield is allowed to change (as a result of a shock). To do this we fit eight models for alternative breakpoints and determine the best fit for a breakpoint where the functional forms switch (table 3.1).

Table 3.1: Models with Breakpoint at Year i

Model 1 (Exponential + Linear-unrestricted)	$log(y) = a_1 + b_1 * year, year = 1940,\ldots,i$ $y = a_2 + b_2 * year, year = i+1,\ldots,2009$
Model 2 (Exponential + Exponential-unrestricted)	$log(y) = a_1 + b_1 * year, year = 1940,\ldots,i$ $log(y) = a_2 + b_2 * year, year = i+1,\ldots,2009$
Model 3 (Linear + Exponential-unrestricted)	$y = a_1 + b_1 * year, year = 1940,\ldots,i$ $log(y) = a_2 + b_2 * year, year = i+1,\ldots,2009$
Model 4 (Linear + Linear-unrestricted)	$y = a_1 + b_1 * year, year = 1940,\ldots,i$ $y = a_2 + b_2 * year, year = i+1,\ldots,2009$
Model 5 (Exponential + Linear-restricted)	$log(y) = a_1 + b_1 * year, year = 1940,\ldots,i$ $y = a_2 + b_2 * year, year = i+1,\ldots,2009$ $s.t.\ \exp(a_1 + b_1 * (t_i + 1)) = a_2 + b_2 * (t_i + 1)$
Model 6 (Exponential + Exponential-restricted)	$log(y) = a_1 + b_1 * year, year = 1940,\ldots,i$ $log(y) = a_2 + b_2 * year, year = i+1,\ldots,2009$ $s.t.\ \exp(a_1 + b_1 * (t_i + 1)) = exp(a_2 + b_2 * (t_i + 1))$
Model 7 (Linear + Exponential-restricted)	$y = a_1 + b_1 * year, year = 1940,\ldots,i$ $log(y) = a_2 + b_2 * year, year = i+1,\ldots,2009$ $s.t.\ a_1 + b_1 * (t_i + 1) = exp(a_2 + b_2 * (t_i + 1))$
Model 8 (Linear + Linear-restricted)	$y = a_1 + b_1 * year, year = 1940,\ldots,i$ $y = a_2 + b_2 * year, year = i+1,\ldots,2009$ $s.t.\ a_1 + b_1 * (t_i + 1) = a_2 + b_2 * (t_i + 1)$

These models imply that the trend function of the data changes once during the whole period at the break year *i*. No restrictions on whether the growth process is linear or exponential and whether the two segments connect are imposed *a priori*. Furthermore, in the estimation we search for the best break point (year) over the period [1959, 1988] (i.e. for *i* in the above equations), excluding the possibility that the change happens in the first or last 20 years. The break point is chosen at the point associated with the smallest mean squared error for the entire model. The estimated results are shown in table 3.2.

Model 2 (Exponential+Exponential-unrestricted) is the best model in terms of mean squared error (MSE).[16] Furthermore, the Ljung-Box test cannot reject the null

[16] We can potentially use other model selection criteria, such as the Akaike information criterion (AIC) or Bayesian information criterion (BIC). These criteria help the researcher to balance goodness-of-fit and parsimony of competing models. The difference in parameter number in our competing model is two at the

hypothesis of random residuals for both segments. This model implies that a break occurred at the year 1973 both to the growth rate and to the yield level. The best fit for the yield growth rate shows it fell from 3.67% before 1973 to 1.75% after, a fall of more than 50%. Such change implies the yield growth rate in more recent periods is approximately one half of what it was before 1973. Two other models are worth noting: Model 1 (Exponential+Linear-unrestricted) and Model 6 (Exponential+Exponential-restricted) exhibit slightly larger MSE but give the same break point (Year 1973). Together, these three models suggest that the trend of corn yield growth of year 1940-1973 is exponential, but that of year 1974-2009 is not as clear— fitted with either linear time trend or exponential time trend the residual can pass the Ljung-Box test. In view of this, we will proceed to the model validation with all three models.

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maximum and only one (if there is a structural break in the data). Furthermore, our best model is not determined solely by one criterion. Therefore, we use the simple criterion MSE only.

Table 3.2: Estimation of Models with Two Segments with Corn Data

Model	Estimation Result	Break Year	Ljung-Box Test (5% Confidence)	Implied Growth Rate		SSE/MSE
				Beginning of the Period	End of the Period	
Simple Linear Model – No break point	a=-3681 b=1.91	--	Fail to Reject	6.57%	1.15%	SSE=5185.20 MSE=76.25
Simple Exponential Model – No break point	a=-37.23 b=0.02	--	Reject	2.10%	2.10%	SSE=7827.75 MSE=115.114
Model 1 (Exponential + Linear-unrestricted)	a_1=-70.51 b_1=0.038	1973	Fail to Reject	3.80%	3.80%	SSE=4492.52 MSE=68.07
	a_2=-3910.6 b_2=2.02		Fail to Reject	2.28%	1.22%	
Model 2 (Exponential + Exp-unrestricted)	a_1=-67.03 b_1=0.03627	1973	Fail to Reject	3.67%	3.67%	SSE=4423.33 MSE=67.02
	a_2=-29.86 b_2=0.01736		Fail to Reject	1.75%	1.75%	
Model 3 (Linear + Exponential-unrestricted)	a_1=-2829.9 b_1=1.47	1964	Reject	5.00%	2.33%	SSE=4619.44 MSE=69.99
	a_2=-28.43 b_2=0.017		Reject	1.70%	1.70%	
Model 4 (Linear + Linear-unrestricted)	a_1=-3791 b_1=1.96	1987	Fail to Reject	6.78%	1.63%	SSE=4630.25 MSE=70.16
	a_2=-5113.7 b_2=2.62		Reject	3.00%	1.59%	
Model 5 (Exponential + Linear-restricted)	a_1=-70.28 b_1=0.038	1967	Reject	3.80%	3.80%	SSE=4750.14 MSE=70.90
	a_2=-3599 b_2=1.86		Fail to Reject	2.33%	1.13%	
Model 6 (Exp + Exp-restricted)	a_1=-71.64 b_1=0.039	1969	Reject	3.90%	3.90%	SSE=4510.35 MSE=67.32
	a_2=-28.08 b_2=0.016		Reject	1.60%	1.60%	
Model 7 (Linear + Exponential-restricted)	a_1=-3680.1 b_1=1.91	1979	Reject	7.50%	1.90%	SSE=4994.98 MSE=74.55
	a_2=-27.05 b_2=0.01598		Reject	1.60%	1.60%	
Model 8 (Linear + Linear-restricted)	a_1=-3080.6 b_1=1.60	1959	Reject	5.54%	3.01%	SSE=5051.53 MSE=75.40
	a_2= -3823.07 b_2=1.98		Fail to Reject	3.62%	1.20%	

Note: SSE stands for Sum of Squared Error. MSE stands for Mean Squared Error. And Year is the year when the data is separated.

To further compare the models, hold-out validation is used. That is, the previous steps are repeated twice with the last 5 and 10 observations excluded from the model estimation and used for prediction. Namely, the simple linear model, Model 1 (Exponential+Linear-unrestricted), Model 2 (Exponential+Exponential-unrestricted) and Model 6 (Exponential+Exponential-restricted) will be estimated again with the data of 1940–2004 and 1940–1999, and used to predict the yields of 2005–2009 and 2000–2009. The estimation results along with the prediction errors are reported in table 3.3.

Although Model 2 (Exponential+Exponential-unrestricted) does not always have the smallest MSE, it is the best among the three in terms of giving the smallest out of sample prediction error. In fact, all except Model 2 under-predict all the yields of 2005–2009 or 2000–2009 (figure 3.4). Furthermore, both the simple linear model and the unrestricted Exponential+Linear model (Model 1) have increasing estimations of the slope coefficient (in their linear parts) when more observations are added in, suggesting that the absolute annual growth in recent years are actually increasing which agrees with the exponential growth process to some extent. Therefore, Model 2 (the unrestricted Exponential+Exponential model) is determined to be the best model for the corn data. After detrending corn data with Model 2, the null hypothesis that the residuals are random cannot be rejected and there is no need to further model the residuals.

Table 3.3: Results of Hold-out Validation with Corn Data- Estimation and Prediction

Model	Estimation Result-0	Estimation Result-5	Out of sample Prediction Error-5	Estimation Result-10	Out of sample Prediction Error-10
Simple Model- No break point *y=a+b*year*	SSE=5185.20 MSE=76.25 a=-3681, b=1.91	SSE=5033.63 MSE=79.90 a=-3629, b=1.88	179.43	SSE=4622.88 MSE=79.70 a=-3588, b=1.86	652.52
Model 1 (Exponential + Linear-unrestricted)	SSE=4492.52 MSE=68.07 Year=1973	SSE=4380.98 MSE=71.82 Year=1973	148.78	SSE=3969.15 MSE=70.87 Year=1973	747.46
	a_1=-70.51 b_1=0.038	a_1=-70.51 b_1=0.038		a_1=-70.51 b_1=0.038	
	a_2=-3910.55 b_2=2.02	a_2=-3746.17 b_2=1.94		a_2=-3521.62 b_2=1.82	
Model 2 (Exponential + Exponential-unrestricted)	SSE=4423.33 MSE=67.02 Year=1973	SSE=4372.19 MSE=71.67 Year=1973	51.27	SSE=4021.97 MSE=71.82 Year=1973	416.07
	a_1=-67.03 b_1=0.036	a_1=-67.03 b_1=0.036		a_1=-67.03 b_1=0.036	
	a_2=-29.86 b_2=0.01736	a_2=-29.80 b_2=0.01736		a_2=-29.52 b_2=0.01722	
Model 6 (Exponential + Exponential-restricted)	SSE=4510.35 MSE=67.32 Year=1969	SSE=4456.07 MSE=71.87 Year=1969	56.09	SSE=4093.48 MSE=71.82 Year=1969	462.11
	a_1=-71.64 b_1=0.039	a_1=-66.03 b_1=0.0357		a_1=-72.56 b_1=0.039	
	a_2=-28.08 b_2=0.016	a_2=-27.84 b_2=0.016		a_2=-26.99 b_2=0.016	
Note: "-5" denotes 5 latest observations (2005–2009) removed from estimation. "-10" denotes 10 latest observations (2000–2009) removed from estimation.					

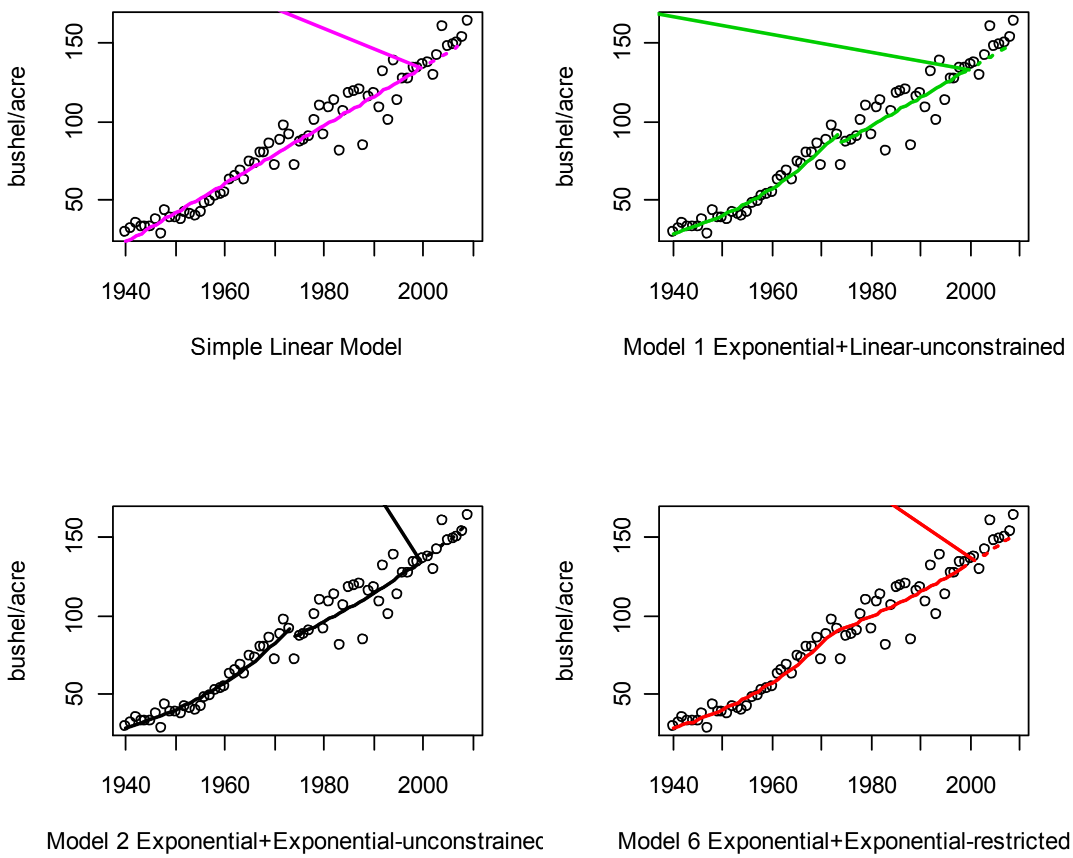

Figure 3.4: Hold-out Validation with Corn Data- Prediction Period of 2000-2009

In addition to corn, the same procedure is applied to data for seven other crops (soybean, wheat, cotton, sorghum, oats, barley and hay) to find out their yield growth trends. Estimation and validation results are presented in Appendix A.[17] Summary of the results is presented in table 3.4. It is found that:

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[17] If the yield data of these crops are transformed with Box-Cox transformation, then the optimal λ's are found to be in the interval of [0,1] for soybean, cotton and barley; furthermore, for soybean, 0, corresponding to an exponential time trend, is within the 95% confidence interval and for cotton and barley, 1 , corresponding to a linear time trend, is within the 95% confidence interval. The optimal λ's for wheat, sorghum, oats and hay are found to be greater 1. Although 1 is within the 95% confidence interval,

(1) Soybeans are the only crop that is well fitted without a break point;

(2) Hay yield grows exponentially until 1982, after which yield growth is zero;

(3) All other crops are best modeled by an Exponential + Exponential model implying that the best fit involves a break point.

(4) After the break point, the growth rates are all found to be lower than the growth rate before that break by 50% or more. Among them, corn and cotton can be better modeled with the unrestricted model which suggests there was shift in the intercept (therefore absolute level of the yield) along with the growth rate; and

(5) The break dates are different across crops.

Table 3.4: Result Summary of Estimated Crop Yield Growth Rates

	No breakpoint	Model 2 Exponential+Exponential_unrestricted with breakpoint		Model 6 Exponential+Exponential_restricted with breakpoint				
Crop	Soybeans	Corn	Cotton	Wheat	Sorghum	Barley	Oats	Hay
Yield Growth Rate Before breakpoint	1.28%	3.67%	3.4%	2.3%	5%	2%	1.8%	1.6%
Break Year		1973	1965	1972	1966	1979	1969	1984
Yield Growth Rate after breakpoint		1.75%	1.5%	0.9%	0.5%	1.0%	0.65%	0.07%

Finally we proceed to test randomness of the residuals from the above best fitted trend functions with a Ljung-Box test. For most of the crops, we find there is no additional information in the residuals. Wheat, sorghum and barley are the crops whose

this indicates that the yields have been growing slower than linearly on average over the whole period and provides some indirect support for the suspicion of declining yield growth rates.

autocorrelations at lag 1 and 2 are statistically significantly different than zero. The non-zero autocorrelation at lag 1 and 2 will be useful for one-step and two-step ahead forecasts (i.e. forecast for yield of the next two year in our context).[18] This result will not be incorporated into our simulation model since it operates on a much longer 10 year time step.

2.2 Testing for Structural Break in US Crop Yields Growth Trend

In this section, we test whether the estimated crop yield growth rates before the break and after the break are statistically different. As explained in the beginning of this section, tests assuming both known and unknown break date will be used.

2.2.1 Test with Known Break Date

When the assumption is made that the break date is known, the Chow test[19] for linear models can be applied to test for constancy of the parameter estimation.[20] For the seven crops that were found to be better modeled with a break point, the null hypothesis of no

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[18] When the autocorrelation (ACF) of a stationary time series (ε_t) is statistically significantly different than zero at lag *j* and the partial autocorrelation (PACF) of ε_t is not statistically significantly different than zero at all lags, it is recommended that ε_t be modeled with MA(*j*), namely $\varepsilon_t = \sum_{i=0}^{j} a_i z_{t-i}$, where $\{z_t\}$ is white noise with mean 0 and variance σ^2 and a_0=1. Let P denote the prediction of ε_t, then $P(\varepsilon_{t+1}) = P(z_{t+1}) + \sum_{i=1}^{j} a_i P(z_{t+1-i})$, where $P(z_{t+1}) = 0$ and $P(z_t) \ldots P(z_{t+1-j})$ can be calculated by observed data. And $P(\varepsilon_{t+j+1}) = P(z_{t+j+1}) + a_1 P(z_{t+j}) + \ldots + a_j P(z_{t+1})$, where $P(z_{t+j+1}) = \ldots$ $_{-1}) = 0$ (Brockwell and Davis 2002).

[19] Chow test is a test of whether coefficients of different linear regression are equal. Suppose the data is $\{(x_1, y_1),\ldots,(x_T, y_T)\}$ and the break date is TB which separate the data into two sub-samples: $\{(x_1, y_1),\ldots,(x_{TB}, y_{TB})\}$ and $\{(x_{TB+1}, y_{TB+1}),\ldots,(x_T, y_T)\}$. To test whether the two sub-samples can be modeled by the same model, first run three regressions: 1) $y_t=a+b*x_t$, $t=1,\ldots,T$; 2) $y_t=a_1+b_1x_t$, $t=1,\ldots,TB$; and 3) $y_t=a_2+b_2x_t$, $t=TB+1,\ldots,T$ and let SSE0, SSE1 and SSE2 denote their sum of squared error respectively. Then the test is defined as $\frac{(RSS_0 - RSS_1 - RSS_2)/2}{(RSS_1 + RSS_2)/(n-4)}$, and under the null hypothesis ($a_1=a_2$, $b_1=b_2$), the test follows F distribution with degree of freedom $(2,n-4)$.

[20] The application is facilitated by the fact that no mixed model (half exponential and half linear) appears among our best models.

structural change is uniformly rejected at the 1% significance level (table 3.5). On this basic we can conclude that that the yield growth changes are statistically different before and after the break or more to the point that yield growth in recent periods is slower than that in the more distant past.

Table 3.5: Chow Test Result of Structural Change in Crop Yield

Crop	Assumed Break Year	Test Value ($F_{0.01}(2,66)=4.942$)
Corn	1973	36.299
Cotton	1965	23.716
Wheat	1972	22.887
Sorghum	1969	72.940
Barley	1979	16.066
Oats	1969	13.441
Hay	1982	73.056

2.2.2 Test with Unknown Break Date

To test for a slowdown in crop yield growth when the break date is unknown, we use the procedure from Ben-David and Papell (1998), which was developed to test for slowdowns in postwar GDP growth. The testing procedure involves two steps: 1) test whether the time series possesses a unit-root, the result of which determines the use of different sets of critical value of the test for structural break; and 2) test for a structural break.

Formally the Ben-David and Papell (1998) procedure is as follows:

Let T denote the sample size and T_B denote the breakpoint year. Then $T_B \in [\alpha T, \beta T]$, where $[\alpha T, \beta T]$ denotes the interval of possible periods at which the change occurs. The parameters α and β are called the trimming parameters and we use the value of 0.25 and

0.75 to correspond the time period during which we search for break point in Section 2.1. Step 1 and 2 involve sequential regression of equations [3.1] and [3.2] respectively:

$$\Delta y_t = \mu + \theta DU_t + \tau t + \gamma DT_t + \delta D(T_b)_t + \rho y_{t-1} + \sum_{j=1}^{k} C_j \Delta y_{t-j} + \varepsilon_t, \forall t \in [\alpha T, \beta T] \quad [3.1]$$

$$y_t = \mu + \theta DU_t + \tau t + \gamma DT_t + \sum_{j=1}^{k} C_j y_{t-j} + \varepsilon_t, \forall t \in [\alpha T, \beta T] \quad [3.2]$$

where in Ben-David and Papell (1998) y_t is the logarithm of GDP per capita and will be replaced with the yield or its log in this study, $DU_t = 1$, if $t>T_B$, 0 otherwise, $DT_t = t - T_B$ if $t>T_B$, 0 otherwise and $D(T_b)_t = 1$ if $t=T_B+1$, 0 otherwise.

Essentially, DU_t and DT_t allow a post break shift in the intercept and the slope in the regression which are captured by (θ-γ*T_B) and γ respectively. In other words, if there is no structural break, then θ and γ would be zero. k, the number of lags, is determined with a data dependent method—start with an upper bound k_{max} of k; if the last lag included in the regression is significant, then use $k= k_{max}$ otherwise reduce k by 1. In this study, k_{max} is set at 5.

For the Step 1 unit root test, let t-stat denote the minimum of the t-statistics on ρ over all possible trend breaks. The null hypothesis (H_0) is that the data follows a unit root process and the alternative (H_1) is the data is stationary. Then according to Perron (1994) H_0 will be rejected if t-stat is less than critical value at the given significance level.

For the Step 2 structural break test, let $SupF_t$ denote the maximum, over all possible trend breaks, of two times the standard F-statistics for testing $\theta=\gamma=0$. The null hypothesis (H_0) is that there is no structural break in the data and the alternative (H_1) is there exists a break. Then according to Vogelsang(1997) H_0 is rejected if $SupF_t$ is larger critical value at given significance level. And $T_B = \underset{t}{arg}\ SupF_t$ gives the estimation of the break date.

Table 3.6 presents the results of the tests assuming the break date is unknown. Columns 2 through 5 correspond to the test statistics results of the two steps and acceptance or rejection of the null hypothesis. Column 6 through Column 10 give numbers resulted from the 2nd step regression. Specifically, Column 6, Column 9 and Column 10 are the break year, the growth rates before the break and changes in the growth rates during the break given by the test regression.[21] The results agree with the Chow-test result. All the crops in our study, except soybeans, exhibit a break point in their yield growth and again we find a statistically significant slow-down in growth rates.

Table 3.6: Test with Unknown Break Date Result of Structural Change in Crop Yield

1	2	3	4	5	6	7	8	9	10
Crop	Stage1 t-stat	Unit Root	Stage2 $SupF_t$	Break	Year of $SupF_t$	Initial Intercept μ	Intercept Shift $\theta- \gamma*T_B$	Initial Slope τ	Slope Shift γ
Soybean	-8.20	No	5.90	No	--	--	--	--	--
Corn	-9.51	No	73.45	Yes	1972	-80.65	51.172	0.043	-0.026
Cotton	-6.79	No	38.13	Yes	1965	-83.40	60.635	0.046	-0.031
Wheat	-6.29	No	21.76	Yes	1968	-77.54	51.278	0.042	-0.026
Sorghum	-6.75	No	27.16	Yes	1966	-102.71	96.249	0.054	-0.049
Barley	-5.54	No	15.72	Yes	1982	-58.34	31.632	0.032	-0.016
Oats	-7.74	No	37.66	Yes	1971	-44.49	33.407	0.025	-0.017
Hay	-6.32	No	20.94	Yes	1982	-22.67	21.772	0.012	-0.011

[21] The estimation results can roughly be interpreted in this way. To obtain the annual growth rates, the estimated slopes need to be adjusted by the parameters on the lags. Also the test is developed mainly for testing of structural break, and there are other specific regressions developed for estimating the break date.

2.3 Conservative Estimation of the Yield Growth Rates

We also derive a conservative estimate of the crop yield growth rate for use in our analysis, i.e. based on trends in the historical data, a growth rate that can be reached with probability of 0.9. With the break point identified, the time trend function for the period 1940-2009 can be written in the following ways:

$$y_t = a_1 + (a_2 - a_1)D_T + b_1(1 - D_T)t + b_2 D_T t \quad [3.3]$$

$$y_t = a_1 + b_1[D_T T_0 + t(1 - D_T)] + b_2(t - T_0)D_T \quad [3.4]$$

Equations [3.3] and [3.4] are for the unrestricted and restricted models respectively. y_t is the logarithm of crop yields. T_0 is the break year and $D_T=0$ if $t \le T_0$ and $D_T=1$ if $t > T_0$. b_1 and b_2 are the annual increase in the logarithm of yield for the first period and second period respectively. By estimating equations [3.3] and [3.4], we obtain the estimated standard error of b_2 $\hat{\sigma}$. Then, based on the delta method, the conservative estimation of crop yield growth rate is

$$ConservativeGrowthRate = \left(e^{\hat{b}_2} - 1\right) - Z_{0.9}\sqrt{\hat{\sigma}^2 \left(\frac{\partial\left(e^{b_2} - 1\right)}{\partial b_2}\right)^2} \quad [3.5]$$

In equation 3.5, $Z_{0.9}$ is the one-tailed critical value at a 90% confidence level for the standard normal distribution. Estimates of other confidence levels can be calculated by simply replacing the critical value at the corresponding confidence level. We present the “Best Guess” of the crop yield growth rates, which are our estimations in previous sections, and the growth rate estimates at “90% Confidence” and “95% Confidence” in table 3.7.

Table 3.7: Conservative Estimation of Crop Yield Growth Rate for the Post-2009 Period

	Soybeans	Corn	Cotton	Wheat	Sorghum	Barley	Oats	Hay
Best Guess	1.28%	1.75%	1.47%	0.90%	0.50%	0.90%	0.65%	0.00%
90% Confidence	1.22%	1.54%	1.32%	0.80%	0.34%	0.80%	0.50%	0.00%
95% Confidence	1.20%	1.48%	1.28%	0.77%	0.29%	0.77%	0.46%	0.00%

3. Exploration of the Implications of Slowdown in Yield

The importance of technological progress can be shown with a simple graphic analysis (figure 3.5).

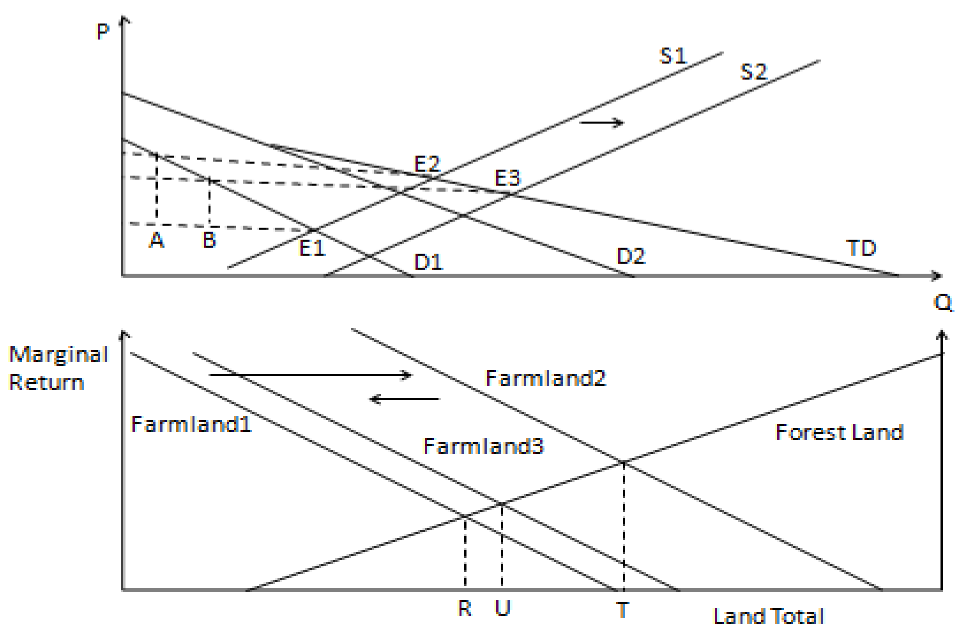

Figure 3.5: Graphic Analysis of Commodity and Land Market

In figure 3.5, the upper panel represents the commodity market and the lower panel represents the land market. The land market representation is adopted from (Mendelsohn and Dinar 2009). Bioenergy policy constitutes a positive demand shock while climate mitigation policy constitutes a negative supply shock in the commodity market. To make the graphical analysis clear, we use a positive demand shock (D2). D1 represents the pre demand shock crop demand; total demand TD after the shock is the horizontal sum of D1 and D2. The market equilibrium is E1 without D2. Adding in D2 without increasing supply moves the market equilibrium to E2. Price increases from P0 to P2, the quantity devoted to the pre shock demand decreases by AE1. In the land market (lower panel), the demand shock would cause farmland acreage to increase from OR to OT. If at the same time there is an increase in supply shifting S1 outwards to S2 to counteract the demand increase, with the result that the raise in market price and reduction in traditional demand would be less by P1P2 and AB and development of new land by for example conversion of forest land is reduced by UT. It is possible for the final equilibrium B and U in both markets to be on the left of the original point E1 (opposite to A and T) and R if the shift in supply is large enough; however, the shift required to make BE1 to be zero is very likely to be different than that required to make UT to be zero.

Viewing the process in a dynamic way, then S1 represents supply under current technological in each period and S2 represents the supply with higher yield growth rate induced by technology progress. The distance between S1 and S2 will increase over time; or in other words, S2 is moving away from S1. However, how fast and how far S2 moves in the real world cannot be determined in this highly abstract graphical model. We now proceed to quantity these effects with a global agricultural simulation model.

3.1 Introduction of the Simulation Model

The global agricultural simulation model is the integration of the US FASOM (Forest and Agricultural Sector Optimization Model) and GLOBIOM (Global Biomass Optimization Model). The integrated model is a recursive dynamic, nonlinear programming model of the global forest and agricultural sector. It simulates the allocation of land over time to competing activities in both the forest and agricultural sectors and the resultant consequences for the commodity markets supplied by these lands. It is a bottom-up global model, being able to take into account not only the economic aspects, but also the biophysical aspects of the sector and therefore lending itself to policy analysis of international environmental issues. More detailed description can be found in Chapter 2.

3.2 Scenario Setup

We use the projections from the Annual Energy Outlook 2009 (AEO) by US Energy Information Administration as our baseline and the Renewable Fuel Standard as our reference policy scenario. The major difference between AEO 2009 and RFS is that the projected level of US conventional ethanol production/consumption is 2 billion gallons less each year in the AEO projection. Our simulation period is from 2000 to 2030. We will simulate using the four technical progress scenarios developed above and see what effect they have on the global sector with and without the US RFS in place (table 3.8).[22] The differences of crop yield growth rates across scenarios are substantial: crop yield

[22] Crop yield growth rates estimated in Section 2 are used for the US, for rest of the world, crop yield rates are set at 0.5% per year.

growth rates in Low Tech are 0.1%~0.2% lower than those under the Current Tech most of which are less than 50% of those in Hi Tech except for soybeans.

Table 3.8: Simulation Scenarios

	Policy Scenario	
Technical Progress Scenarios[23]	Baseline (AEO)	RFS
Low Tech: Crop yields grow at conservative rates, estimates with 90% confidence	AEO.LOW	RFS.LOW
Current Tech: Crop yields grow at current rates	AEO.BASE	RFS.BASE
Hicorn Tech[24]: Corn yield grows at historical high rate and other crops grow at current rates	AEO.HICORN	RFS.HICORN
Hi Tech: All crop yields grow at historical high rates	AEO.HI	RFS.HI

3.3 Simulation Results

3.3.1 Effect on Domestic Production, Price and Welfare

We begin with presenting the breakdown in corn usage (table 3.9). In the Low Tech and Current Tech scenarios, the implementation of RFS causes corn for traditional use to shift away toward ethanol-- corn quantities for domestic demand, feed mix use and

[23] In our estimation, the logarithms of crop yield data are regressed on year, namely $log(y_t)=a+bt+\varepsilon_t$, in which b can be interpreted as the crop yield growth rate. It follows that the expectation of logarithem of crop yield is $E(log(y_t))=a+bt$ and the expectation of crop yield is $E(y_t)=e^{a+bt+\frac{\sigma^2}{2}}$, where σ^2 is the variance of the error term. The term $e^{\frac{\sigma^2}{2}}$ is neglected in our calculation of crop yield forecasts. Since the estimated σ^2 is in the order of 10^{-2}, our ignorance will result in a difference less than 1%.

[24] This scenario is included because the sources of R&D investments in developing better seeds are different among the crops. Development of corn seeds receives a lot of investment in the private sector, followed by soybeans and cotton. But that of wheat and other smaller crops rely on researches in public institutions (Fernandez-Cornejo 2009). Because public research is generally less sensitive to price and also it is found that public investment in agricultural investment is slowing down in existing literature (Alston et al. 2009), it is very likely that technology progress occurs to only some of the crops we examined in previous section.

export decrease and that for process use (which includes making ethanol) increases. In the Hicorn Tech and Hi Tech scenarios, corn quantities for all usages are higher even with the implementation of RFS policy.

Table 3.9: Difference in Categories of Corn Demand in US Relative to Scenario AEO.BASE in Million Bushels

	Export			Domestic Demand			Feed Mix Use			Process Use		
	2010	2020	2030	2010	2020	2030	2010	2020	2030	2010	2020	2030
RFS. LOW	-39.8	-95.1	-467.3	-15.5	-23.7	-15.3	-267.1	-319.0	-80.4	670.4	905.6	534.1
RFS. BASE	-12.7	-19.9	-297.8	-15.5	-15.8	0.0	-173.5	-19.7	78.5	670.7	922.2	546.3
RFS. HICO RN	170.0	771.3	550.9	38.8	86.7	68.7	699.3	1276.2	924.9	734.3	1006.1	631.7
RFS. HI	170.0	1274.0	1579.4	38.8	86.7	68.7	547.7	1124.0	631.8	734.3	1002.1	610.4

With the exception of soybean, the implementation of RFS policy also causes decreases in productions of other crops for the period 2010 under the Low Tech and Current Tech scenarios due to acreage substitution and lower prices (upper panel of figure 3.6). In the medium term, namely at the end of our simulation period the effect of the RFS policy on crop productions is much smaller than the effect of technology progress (lower panel of figure 3.6). Regardless of the policy scenario, under the Low Tech scenario and Current Tech scenario the quantities of corn and soybeans increase by around 80% and 40% respectively for the simulation period 2030. In the Hicorn Tech scenario and Hi Tech scenario, corn production doubles at the end of the simulation period. Soybean production increases by 20% in the Hicorn Tech scenario, which is the smallest among all the technology scenarios. Production of other crops also experience less increase or even decrease in the Hicorn Tech scenario. This may be due to the fact that profitability of corn is better due to higher technological progress, and therefore other crops are crowded out. The Hi Tech scenario is the only scenario that productions of all crops show positive increase.

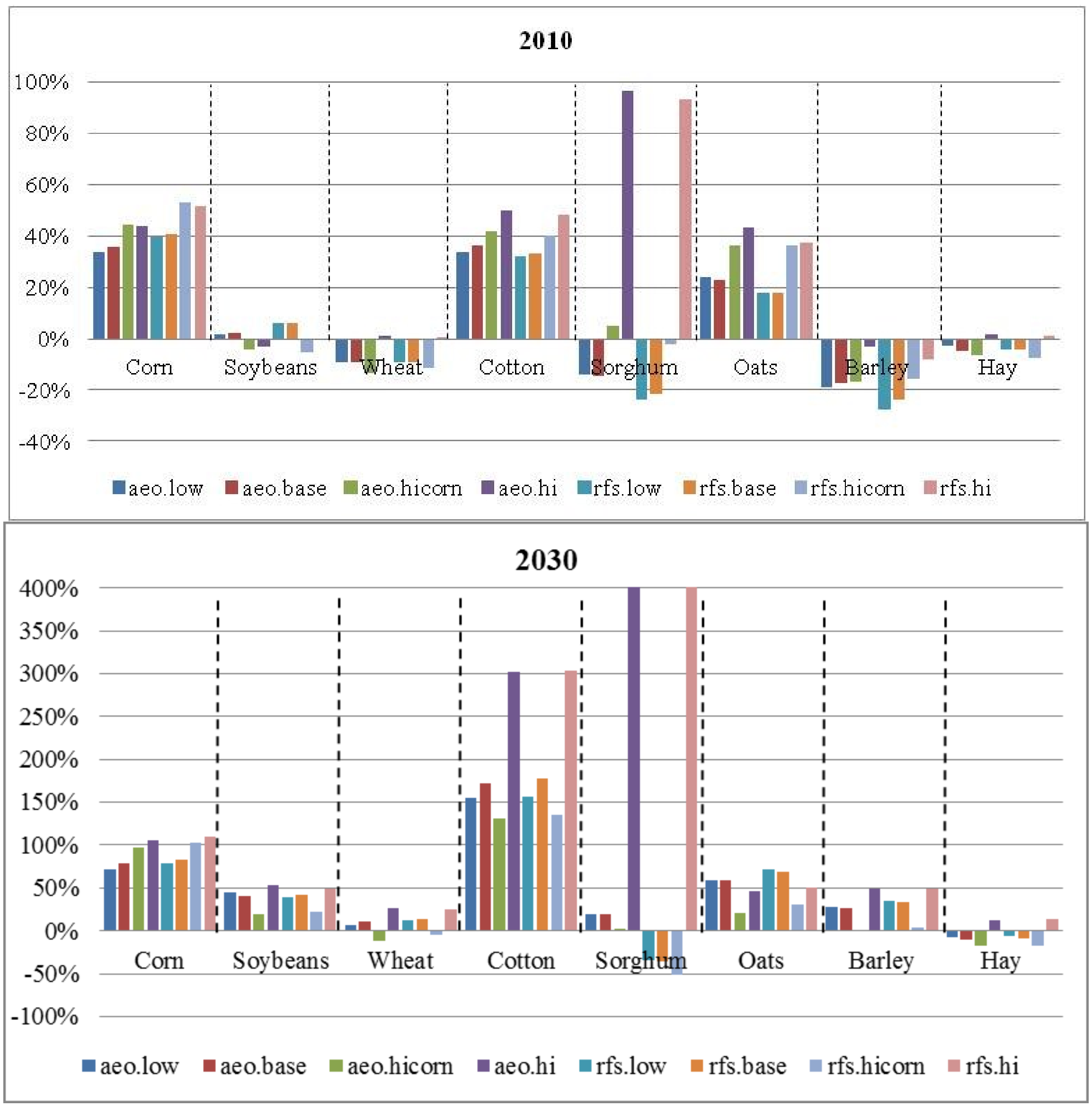

Figure 3.6: Percentage of Production Increase Relative to 2000 of All Crops

The Fisher index of US domestic prices of the eight crops are presented in table 3.10. Under the AEO.LOW and AEO.BASE scenario, the values of the index are larger than one for the whole simulation period, reflecting that the supply and demand balances are tight during the simulation period without the RFS policy. The presence of the RFS policy causes more price increases. In the Hicorn Tech scenario, prices return to the 2000 level at period 2020 but increase by 10% at period 2030. This may be caused by the prevailing limited increase/ reduction in productions of crops other than corn. Only in the Hi Tech scenario, prices show decreasing trend.

Table 3.10: Fisher Index of US Domestic Prices of the Eight Crops

	2000	2010	2020	2030
AEO.LOW	1	1.18	1.12	1.07
AEO.BASE	1	1.17	1.10	1.07
AEO.HICORN	1	1.07	1.02	1.13
AEO.HI	1	0.99	0.83	0.76
RFS.LOW	1	1.22	1.16	1.07
RFS.BASE	1	1.20	1.13	1.06
RFS.HICORN	1	1.08	1.01	1.12
RFS.HI	1	1.00	0.82	0.76

Total domestic welfare is higher with the presence of the RFS policy and also increases with higher yield growth rates. Furthermore, although decomposing the change of welfare to technology progress and policy depends on the route of the decomposition, it is robust that the impact of the RFS policy is larger than that of change in crop yield growth rates (table 3.11).

Table 3.11: Decomposing Total US Agricultural Sector Welfare (In Billion US Dollars)

Initial Scenario	Difference between Initial Scenario and Medium Scenario			Medium Scenario	Difference between Medium Scenario and End Scenario			End Scenario
	2010	2020	2030		2010	2020	2030	
AEO.BASE	-0.6	-1.3	-1.2	AEO.LOW	1.7	14.0	15.0	RFS.LOW
	1.6	13.3	15.0	RFS.BASE	-0.6	-1.4	-1.2	
	3.6	4.1	2.8	AEO.HICORN	0.6	14.3	15.0	RFS.HICORN
	1.6	13.3	15.0	RFS.BASE	3.4	5.1	2.5	
	6.0	11.1	13.2	AEO.HI	1.7	14.7	16.0	RFS.HI
	1.6	13.3	15.0	RFS.BASE	6.0	12.6	14.1	

Consumers generally lose with the presence of the RFS policy but gain with increases in crop yields. All regions but Western_US gain increase in surplus with the implementation of the RFS policy. Technology progress tends to cause losses to producers. Under the Hi Tech scenario, 3 out of 5 regions (Western_US, Southern_US and Midwest) will incur surplus loss. But some of these losses can be outweighed by the gains brought by the RFS policy. For example, Midwest would gain 12549.6 million US dollars with the implementation of RFS, and if crop yield growth rates were resumed to the Hi Tech scenario level, the surplus gain would reduce by 4575.5 million US dollars--net effect of the policy and technology progress remains positive (table 3.12).

Table 3.12: Decomposing Regional US Agricultural Sector Producer Surplus (In Million US Dollars)

	LOW		BASE		HICORN		HI	
	Difference between RFS. BASE and AEO. BASE	Difference between different technology progress and BASE with RFS	Difference between RFS. BASE and AEO. BASE	Difference between different technology progress and BASE with RFS	Difference between RFS. BASE and AEO. BASE	Difference between different technology progress and BASE with RFS	Difference between RFS. BASE and AEO. BASE	Difference between different technology progress and BASE with RFS
WESTERN_US	-1590.3	52.4	-1590.3	--	-1590.3	6472.8	-1590.3	-1454.2
PLAINS	17697.4	828.5	17697.4	--	17697.4	7006.6	17697.4	345.2
SOUTHERN_US	1376.2	-595.0	1376.2	--	1376.2	2293.7	1376.2	-5159.8
MIDWEST	12549.6	339.7	12549.6	--	12549.6	-7090.7	12549.6	-4575.5
NRTHEAST	32.7	92.2	32.7	--	32.7	-73.1	32.7	696.8

3.3.2 International Leakage Effect

The aggregate impact of the RFS policy and technology progress in US on the total welfare of rest of the world is quite small. We will briefly discuss the impacts on production and then turn our attention to the leakage effect.

World demand is growing all the time. If crop yield growth rates in the US decrease (increase), prices would rise and this would stimulate increases (decreases) in production in the rest of the world. The model results show this. Under the Hi Tech scenario, production of corn, wheat and sorghum increase in the US causing prices to drop and in turn production in the rest of the world decreases. Production of corn in the rest of the world is the lowest in the Hicorn Tech scenario and that of other crops are the same as in the Current Tech scenario. Soybeans production is higher in the Hi Tech scenario and the Hicorn Tech scenario than that in the Current Tech scenario.

Table 3.13 shows the differences in land use change among some of the scenarios. Under the Current Tech scenario, the implementation of RFS policy in the US would cause increases in the acreage of agricultural land (cropland, grassland or short rotation coppice (SRP) production) over the whole simulation period, total at 1.16 million hectares. This land is converted from 0.25 million hectares of deforestation and 0.91 million hectares of natural land. Furthermore, a 0.1%-0.2% reduction in crop yields (i.e. moving from Current Tech scenario to Low Tech scenario) would cause additional of land converted for agricultural use increase to 1.81 million hectares, which is a more than 50% of increase. If all crop yield growth rates were resumed to historical high level, agricultural land use increases reduce by 0.66 and 2.83 million hectares in 2010 and 2020. Agricultural land use sees a large increase in the period of 2030. Together, a smaller but positive leakage effect-- a total of 0.16 million hectares less of land conversion—is resulted over the whole simulation period. The Hicorn scenario shows a similar story and the leakage effect is even smaller (0.30 million hectares) over the whole simulation period.

Table 3.13: Comparative Levels of International Land Use Change (Million Hectares)

		1	2	3		4	5		6	
Scenarios compared		Cropland	Grassland	SRP	**Subtotal of 1, 2, and 3**	Primary Forest	Managed Forest	**Subtotal of 4 and 5**	Natural Land	**Subtotal of 4, 5, and 6**
RFS.BASE less AEO.BASE	2010	0.67	-0.03	-0.01	0.63	-0.26	-0.03	-0.29	-0.34	-0.63
	2020	0.45	0.03	0.02	0.51	0.34	-0.01	0.32	-0.83	-0.51
	2030	-0.27	0.16	0.13	0.02	-0.33	0.04	-0.29	0.27	-0.02
	Cumulative	**0.85**	**0.16**	**0.14**	**1.16**	**-0.25**	**0.00**	**-0.25**	**-0.91**	**-1.16**
RFS.LOW less AEO.BASE	2010	0.83	-0.06	-0.01	0.76	-0.44	-0.03	-0.47	-0.29	-0.77
	2020	0.97	0.06	0.05	1.08	0.39	-0.18	0.21	-1.30	-1.09
	2030	-0.27	0.27	-0.03	-0.03	-0.21	-0.06	-0.27	0.30	0.03
	Cumulative	**1.53**	**0.27**	**0.01**	**1.81**	**-0.26**	**-0.27**	**-0.53**	**-1.29**	**-1.82**
RFS.HICORN less AEO.BASE	2010	-0.23	-0.05	0.01	-0.27	0.56	0.00	0.56	-0.29	0.27
	2020	-1.69	-0.20	-0.12	-2.01	0.92	1.31	2.23	-0.23	2.00
	2030	1.97	0.76	-0.15	2.48	-0.58	0.47	-0.11	-2.47	-2.58
	Cumulative	**0.05**	**0.51**	**-0.26**	**0.30**	**0.89**	**1.78**	**2.67**	**-2.98**	**-0.31**
RFS.HI less AEO.BASE	2010	0.01	-0.02	-0.01	-0.02	1.10	0.00	1.10	-1.08	0.02
	2020	-1.93	-0.19	-0.10	-2.82	1.20	1.54	2.74	-0.52	2.22
	2030	2.78	0.51	-0.05	3.84	-1.27	0.43	-0.78	-2.41	-3.19
	Cumulative	**0.86**	**0.30**	**-0.16**	**1.00**	**1.03**	**1.97**	**3.00**	**-4.01**	**-1.01**

Note: Land can be converted in and out of Category 1, 2, 3. No land can be converted into Category 4 and 6. No land can be converted out of Category 5. Therefore, positive (negative) denotes more (less) land converted into one category or less (more) land converted out of one category depending on the specific category.

The reduction of leakage effect with higher crop yield growth rates happens only at the highly aggregate level. Although avoided deforestation is larger in scenarios with higher crop yield growth rates, the conversion of natural land is also higher. Furthermore, some specific regions could have increase in forest clearance in scenarios with higher crop yield growths (figure 3.7).

Under the Current Tech scenario, the implementation of the RFS causes an addition of 322 million metric of GHG emissions associated with land use change. This estimation is quite close to the estimate by Mosnier et al. (2012), which uses the GLOBIOM model alone. In that paper, estimates are further normalized based on simulation period and production and energy contents of the bioenergy and then compared to other studies.[25] However, it is not very clear whether the results across the studies are directly comparable as the normalization procedure is not explicitly presented in most of these studies. Small reductions in crop yield growth rates lead to an 80% increase in emissions. Our result shows that the Hicorn scenario in which corn is the only crop whose growth rate was resumed to its higher historical level is preferable in terms of GHG emissions. Avoided GHG emissions in RFS.HICORN scenario is larger than that in the RFS.HI scenario and RFS.HICORN is the only technology scenario under which cumulative GHG emissions over the whole simulation period is smaller than that in the AEO.BASE scenario (table 3.14).

[25] In most studies, the leakage effect in terms of GHG emission is presented in grams/MJ (or grams/BTU), in which MJ and BTU stand for mega joule and British thermal unit respectively. These numbers are obtained through normalizing the total emission in the following way: $\frac{TotalEmission}{DifferenceIn\ Pr\ oductionOfBioeneryBetweenBaseAndPolicyScenarios * EnergyContentOfBioenergy}$ .In some studies, the number would be further annualized. Therefore, the results are determined not only by the simulations, but also by the post-simulation report calculation procedures, which are very likely to differ across studies.

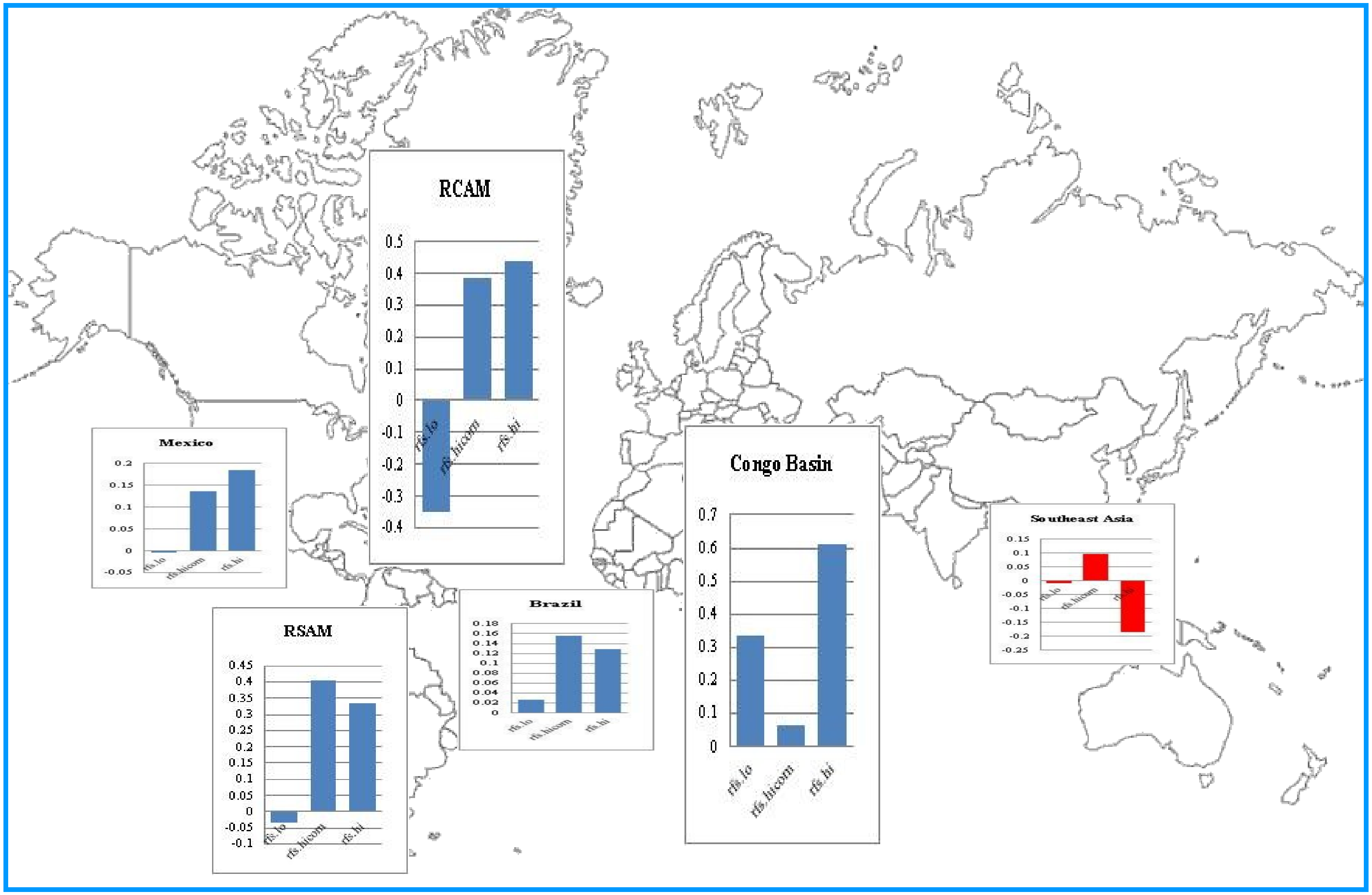

Figure 3.7: Difference in Avoided Deforestation Relative to Scenario RFS.BASE (For Regions with More Than 0.1 Million Hectares Difference)

Table 3.14: Difference in GHG Emissions Associated with Land Use Change (Million Metric Tonne)

	RFS.BASE less AEO.BASE	RFS.LOW less RFS.BASE	RFS.HICORN less RFS.BASE	RFS.HI less RFS.BASE
2010	36.09	-28.63	-186.31	-201.49
2020	84.80	-32.75	-247.39	-79.46
2030	201.93	320.94	-741.22	22.89
Cumulative	**322.82**	**259.56**	**-1174.92**	**-258.06**

4. Conclusion and Limitations

This paper has examined the yield growth trend of 8 major US crops and found that all but soybeans has experienced slowdown during the period of late 1960s to early 1980s. In particular corn has fallen from 3.67% to 1.75%. The reductions in crop yield growth rates are tested to be statistically significant.

We use the estimation results to investigate the international effect of the US bioenergy policy (the Reusable Fuel Standard) under alternative yield scenarios. The policy has been subject to criticism as it competes with traditional demand and contributes to price rises and can stimulate undesirable environmental consequences, notably land use changes. We have found that if US crop yields grow at the current rate, the supply-demand balance would be tight even without the bioenergy policy as the price index remains larger than one for the whole simulation period. And the implementation of the policy will cause price to further increase.

If US crop yields grow at the current rate, the implementation of RFS has strong impacts in the short-run-- corn for all uses but processing reduces and corn production crowds out productions of other crops. In the medium term, the impacts of the RFS policy on production are much smaller than that of technology progress.

Total welfare increases with the implementation of the RFS policy and also with higher technology progress. Decomposition of the total welfare shows that a larger part of the increase should be ascribed to the policy implementation. Producers generally gain with the policy implementation and lose with higher crop yield growth rates. The net effect of policy and technology progress is uncertain for individual regions.

The implications on land use change are more complicated. Our model shows that if US crop grows at the current rate, the implementation of RFS policy would cause an addition of 1.16 million hectares of agricultural land expansion in rest of the world, which comes from deforestation and loss of natural land. And slowing in crop yield growth rates leads to large increases in clearance of forest and natural land. The net land use change from forest/natural land to agricultural land in rest of the world would be smaller but remain positive if US crop yield growth were resumed to the historical high level. Furthermore, specific regions could incur increase of forest/natural land clearance in scenarios with higher crop yields. The different spatial distributions of land use change make it difficult to calculate the environmental benefits of higher crop yield growth rates, especially when local benefits of these land types are considered.

Associated with land use change, GHG emissions is smaller in scenarios with higher crop yield growth rates. Specifically, our model shows that the leakage effect in terms of GHG emission is negative in the Hicorn scenario in which only corn yield growth rate was resumed to its higher historical level. However, this result may be sensitive to the simulation period choice as we see large increases in both prices and acreage of agricultural land at the end of our simulation period.

There are several limitations to this analysis that we should point out. First, our results on GHG emission cannot be viewed as a complete emission assessment of the bioenergy policy. Within the agricultural sector, our calculation focuses on those related to land use change and does not take emissions related to fertilizer into account. Fertilizer-related emissions would differ across scenarios for two reasons: firstly, level of fertilizer use is a part of management decision to be endogenously determined at each solve of the model; and, secondly, since positive input elasticities ε are specified in the integrated FG model, meaning that 1 % in yield increase implies ε% of increase in fertilizer use (and the rest of $(1- \varepsilon)$% is due to pure technological progress), fertilizer use would vary across different technological progress scenarios. Moreover, simulation results are subject to limitations in the modeling exercise discussed in Chapter II so are better thought of as qualitative estimates of the likely magnitude and direction of trends, than of quantitative predictions of the actual values of those trends.

The most important conclusion is that with higher technological progress, it would be possible for the agricultural sector to meet the new demands stemming from the need of climate change mitigation and the traditional demands simultaneously. However, whether this can be achieved depends on not only the rates of technological progress (namely crop yield growth rates in this study) but also the mix of technological progress of different crops.

CHAPTER IV

DESIGNING POLICIES TO ADDRESS ADDITIONALITY

1. Introduction and Literature Review

Because of the positive externality of environmental services, they are often under-produced. One way to correct for it is for governments to pay for the environmental services provided. Farmers in the US have been paid to adopt practices that generate environmental services through programs such as the Conservation Reserve Program (CRP), which started in 1985. In recent years, international conservation agencies and developed countries have increasingly turned to incentive-based approaches, especially direct payments for environmental service, to replace the method that nests stimulation of environmental good production in development supporting, for example the Integrated Conservation and Development programs (Ferraro and Kiss 2002). The popularity of direct payment programs arises in the background of which agencies are facing tightening budgets and pursue more efficient use of limited financial resources (Ferraro and Kiss 2002, Wunder 2005).

It is very difficult to measure the benefits of these programs precisely for reasons such as uncertainty or the existence of intangibles. What can be said with certainty, however, is that if a payment does not generate any benefits, it fails the most basic test of economic efficiency. It turns out that all environmental programs must address this critical question: are the payments bringing about positive changes; i.e., is there sufficient *additionality*? Additionality is satisfied if payments are made for services that would not have occurred without the payment.

The issue of climate change mitigation is one area where additionality has received a lot of attention in recent years. It has been estimated that there could be low cost mitigation opportunities (in the form of emission reductions and carbon sequestration) in the agricultural and forestry sectors (Manley, et al. 2005, McCarl and Schneider 2001, Sohngen, et al. 2008). Cap-and-trade schemes have been popular in the international community for controlling greenhouse gas emissions. However, as the agricultural and forestry sector is not very likely to be covered by a cap (with some possible exceptions), these low cost opportunities are likely to be included in the carbon market as *offsets*. The idea of offsets is that a capped emission source can neutralize its own emission by paying for emission reductions in regions or sectors that are not under the cap.[26] However, if the offsets generated are non-additional, i.e. they would have happened even without the payment, then the crediting and sale of these offsets would not reduce emissions relative to the status quo and the trade would result in increase in GHG emissions.

The non-additionality problem stems from asymmetric information between those who credit and pay for the environmental service and those who provide it. To completely avoid making payment to the non-additional environmental service produced,

[26] For example, under the Kyoto Protocol, offsets are allowed through the mechanisms of Joint Implementation (JI) and Clean Development Mechanism (CDM).

buyers need to know the specific baseline of every producer,[27] but individual baselines are more likely to be private information of the producers.[28] The information advantage of the service producers enables them to gain some rents by selling the non-additional environmental service. While from the standpoint of the buyer, it would be more costly for her to attain any given amount of additional environmental service.

A policy design that regulators frequently use to avoid paying for the non-additional production is the baseline method. This method refers to a policy design in which the regulator sets a baseline and pays every producer for production above the baseline.[29] By doing so, the regulator will not be able to weed out all the non-additional service unless the announced baseline is set at the maximum baseline of the whole group of producers who participate. At the same time, she potentially penalizes some producers who have a low baseline, so that some low cost production is excluded. The baseline method has been studied in both empirical (Ghosh et al. 2011) and theoretical studies (Horowitz and Just 2011). Ghosh et al. (2011) uses a simulation model with real data and shows credit supply decreases with tightening baseline in the water quality trading program of the Conestoga watershed. Horowitz and Just (2011) examines the determination of an optimal baseline in the context of carbon cap-and-trade scheme where the baseline is applied to a source uncovered by the cap and in turn this source

[27] That is, buyers need to know not only the distribution of the baselines, but the individual realizations of baselines for each offset producer. The distribution itself may be difficult to anticipate, but the implications of unknown baseline distribution are beyond of the scope of this paper.
[28] We will use the term “producer” to exclusively refer to a non-capped source that produces offset to the market. The term “buyer” will generally refer to a government agency that is subsidizing the creation of offsets, though in some contexts it can refer to a capped source in a cap-and-trade program that desires to buy offsets to some of its emissions.
[29] In a pollution abatement context, it would be the polluter will be awarded if his emission is less than the baseline and the award depends on the difference between the smaller actual emission and the baseline.

generates and sells offsets to the capped sectors. In their study, the baseline refers to a baseline of emission, whch is the negative of environmental service of emission abatement. With the objective of maximizing the surplus of both the offset seller and buyer minus damage to the environment, they find that whether the optimal baseline would be smaller than the expected business as usual depends on the trade-off between the damage of non-additional emissions and the benefit of cost savings and it is generally desirable to set a baseline lower than the expected business as usual. This finding is contrary to the study on the voluntary opt-in component of the sulfur dioxide emission trading program in Montero (2000). Montero(2000) favors a low baseline, which allows payments for non-additional production and contradicts with the purpose of ensuring environmental integrity. Essentially, a low baseline allows all the low cost abatement opportunities to participate and at the same time the credit producers receive large windfall profits from the credit buyer. This turns out to be efficient because the transfer does not affect the objective, which considers only the total welfare. Both Horowitz and Just (2011) and Montero (2000) directly link the capped sources with the uncapped sources to determine the social optimally optimal level of offsets. However, in reality, the decisions of determining the optimal level of offsets and procuring the offsets are very likely to be made by different entities. For example, in carbon cap-and-trade schemes (and also other air pollution cap-and-trade schemes), the maximum number of offsets that can be used by a capped source is often prescribed before the schemes start to operate and equilibrium prices are formed. In the case of CRP program and international avoided deforestation and biodiversity programs, it is usual that program administrators are endowed with fixed budgeted funding and make decisions only on the procurement of environmental service. In these circumstances, these entities will have narrower objectives that may or may not be equivalent to social welfare maximization. It should be noted that in the baseline method a price (the unit payment) and a quantity (the baseline) are specified; or in other words, the baseline method is a combination of quantity and price policy instruments. If guaranteeing a particular quantity of additional production is the only goal of the regulator, such a combination may not be necessary. The regulator can use a price instrument alone to incentivize the environmental service—i.e. she can set the baseline at zero and buy excessive production, sufficient to ensure that it has procured the given amount of additional production it wants (we will refer this method as "the uniform price method" hereafter). This is equivalent to the use of a discounted price for offsets generated by the agricultural sector in the climate change mitigation context (Kim 2004, Murray et al. 2011).

Which method is preferable depends on the objective of the policy designer. Situated in the context of international avoided deforestation program, van Bentham and Kerr (2011) investigates payment schemes to developing countries by developed countries. That paper suggests there are three objectives that the scheme designer needs to take into account: efficiency,[30] minimization of cost to the service buyer and maximization the extent of additionality.

[30] "Efficiency" has not been explicitly defined in the paper. But equation in the paper suggests: for any forest plot which has non-negative opportunity cost of clearance and has value of positive externality greater than its opportunity cost, if its clearance were avoided because of the direct payment, then efficiency is achieved.

Our paper will take the service buyer's perspective who only values the additional production and seeks to minimize her cost of securing that production. Investigation on the design of PES programs from this perspective is very important. For a lot of PES programs, the service buyer coincides with the regulator who has limited amount of financial resource and her sole goal is to incentivize the supply of environmental services. Since there are always opportunity costs in spending public funding in a specific program instead of others, it would be desirable to make use of this funding as efficiently as possible. If the welfare implications of the transfer from tax payers to the government and the allocation of governmental funding among different programs are not considered, the objective of pursuing cost-effectiveness would be equivalent to that of pursuing social optimum.[31] Cost-effectiveness is always a key aspect in the efficiency of environmental programs. And additionality adds a new dimension to the evaluation of efficiency. Our analysis makes contribution to the ongoing discussion on how to design environmental programs to achieve cost-effectiveness and additionality simultaneously.

In addition to the baseline and the uniform price methods, we will also consider a more complicated design for the regulator to choose, the screening contract method. That method is built on the principal-agent model which is a standard model that explores allocation efficiency under asymmetric information and has been applied in various contexts (Laffont and Martimort 2002). A typical example is the determination

[31] However, in the climate change mitigation context, the service buyer might be an aggregator who bundles offsets generated in the agriculture sector and sells them to the energy sector rather than the designer of the whole cap-and-trade program. In that case the most cost-effective approach may be differ from the socially optimum outcome.

of an optimal pricing strategy of a monopolistic firm who is facing consumers with heterogeneous preferences unrevealed. In this context, the principal is the firm and the agents are the consumers. The resulting optimal pricing strategy is a non-linear pricing schedule that contains different elements. For each consumer, these elements imply negative or positive surplus and the agents will choose the one that maximizes their surplus and their types are revealed consequently. This strategy enables the firm to reduce surplus left to the high value consumers and therefore to make more profits. It is called second degree of price discrimination in the pricing context (Waldman 2004). In the payment for environmental program service context, the principal and the agents are the regulator and the producers respectively. And applying the principal-agent model enables the regulator to reduce rent paid to the low cost producers and therefore to reduce the total payment for incentivizing additional environmental service production. The main difference between the baseline/ uniform price methods and the screening method is whether to discriminate or not.

Several existing studies suggest using screening contract method to improve the cost-effectiveness of environmental service program with heterogeneous service providers (Wu and Babcock 1995, Smith 1995, Wunder 2005, Ferraro 2008). Wu and Babcock (1995) investigates the screening contract design of a green payment program which pays farmers to adopt efficient production practice to use less water and fertilizer. Smith (1995) applies the same model to the CRP program. Mason and Plantinga (2010) explicitly incorporates non-additional production in the cost curves of the producers.

The screening contract method leads to a schedule of prices for different quantities leaving more "degrees of freedom" at the disposal of the regulator. And therefore, there is no wonder that it is more cost-effective (or more profitable) compared to a non-price discrimination strategy. However, a further question that should be answered is: how much better is the screening method? Or in other words, what is the cost effectiveness of these methods relative to each other? This is an important question for the regulator who in reality not only makes payments to the producers but also needs to pay for all the administrative costs associated with the program—the so-called transaction costs. A more complicated policy design would be preferable only when the cost saving from the total payment outweighs the additional transaction costs it entails.

Furthermore, the screening contract method has more than one variant depending on how the regulator specifies the contract. The contract variables may include prices only. For example, the often-used two-part tariff in which the principal specifies a lump sum payment plus a unit charge (Waldman 2004). This variant is also often used in regulation literature (for example, the seminal work by Baron and Myerson (1982)). The contract could also be a combination of quantity and price as used in Laffont and Martimort (2002). These variants are not always equivalent. In the environmental program design literature, both variants have been discussed, for example, Smith (1995) specifies only a unit payment for land retirement while Wu and Babcock (1995) specifies a combination of practice and total payment. But their differences have received little attention.

In all the existing studies the cost saving of the screening contract method is shown with numerical examples and the difference is large in some cases but trivial in others. Analytical development of how the cost saving is related to underlying parameters has not been explicitly explored. In this paper, we set up an analytical model that would enable us to compare the cost-effectiveness across the baseline method, the uniform price method and two variants of the screening contract method (figure 4.1). We consider a situation in which some of the environmental service producers have non-additional production and the regulator, who only values the additional production, knows the distribution but not the realization of the non-additional production. We will define these designs more carefully in the following sections.

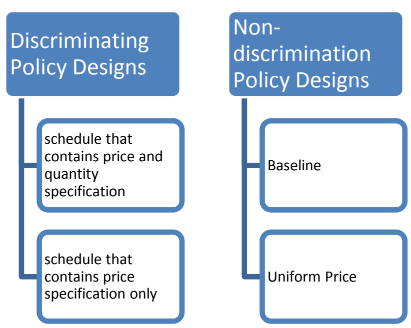

Figure 4.1: Summary of Policy Designs Investigated

We begin with the most abstract two-type model in Section 2. Then we present our results in Section 3. We further extend our analysis to the case in which producers are continuously distributed in Section 4. We conclude the paper in Section 5.

2. Alternative Contract Schemes

2.1 First-best Contracts with Complete Information

We first present the complete information case (i.e. the first-best case) based on which comparison of alternative feasible schemes under asymmetric information could be done. Suppose there is a regulator trying to procure carbon offsets from two types of farmers that supply offsets q_1 and q_2. The producers' costs, C_1 and C_2 are defined by the following total cost curves:

$$C_1(q_1,\theta_1)=\theta_1(q_1-\tilde{\zeta} \text{ with } \theta_1>0 \text{, if } q_1>\tilde{\zeta}\text{; } C_1(q_1,\theta_1)=0 \text{, if } q_1\le\tilde{\zeta} \quad [4.1]$$

$$C_2(q_2,\theta_2)=\theta_2 q_2^2 \text{ with } \theta_2>0 . \quad [4.2]$$

In what follows, we refer to those with total cost curves [4.1] as "Non-additional producers" since they have zero cost for the first $\tilde{\zeta}$ unit of production and "Additional producers" are those with total cost curve [4.2] who incur positive cost for each unit of its production. Non-additional producers would provide $\tilde{\zeta}$ without any incentive so $\tilde{\zeta}$ is also called the business-as-usual production. For the reason of convenience, we will assume that $\theta_2=a\theta_1, a\in[1,+\infty)$, so that the marginal costs of the additional producers is weakly greater than that of the non-additional producers. The failure of this assumption would complicate the solution to the discriminating design problems. We will briefly discuss the implications of relaxing this assumption at the relevant points below. Then their marginal cost curves are respectively (figure 4.2):

$$MC_1=2\theta_1(q_1-\tilde{\zeta} \text{ if } q_1>\tilde{\zeta}\text{; } MC_1=0 \text{ if } q_1\le\tilde{\zeta} \quad [4.3]$$

$$MC_2 = 2\theta_2 q_2 \, . \qquad [4.4]$$

For typical goods in a market with one Non-additional producer and one Additional producer, the market supply Q associated with a price p would be

$$Q = p\left(\frac{\theta_1 + \theta_2}{2\theta_1\theta_2}\right) + \tilde{\zeta} \, . \qquad [4.5]$$

But for environmental goods, the first $\tilde{\zeta}$ supplied by the non-additional producers should not be considered as offsets because they do not satisfy the requirement of additionality.

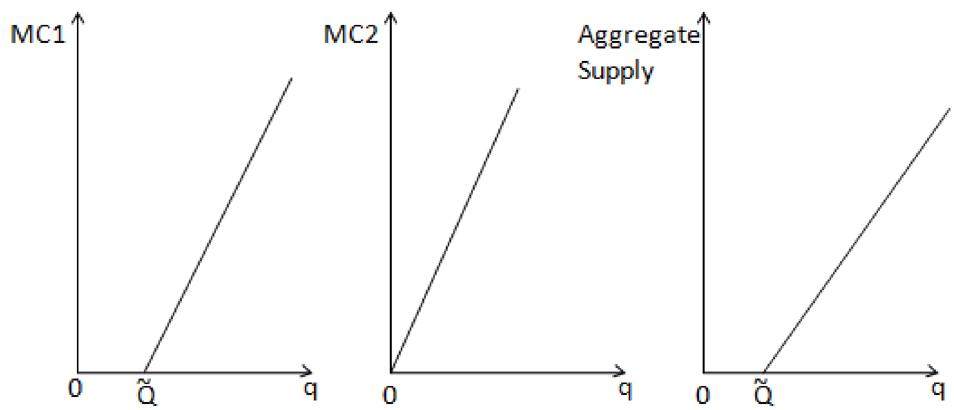

Figure 4.2: Marginal Cost and Supply Curves

If the regulator has complete information over the producers' costs, i.e. she knows who is associated as which cost curve, then she could design a "take it or leave it" quantity-payment contracts for the two producer types, (q_1, T_1) and (q_2, T_2). We will generalize by allowing the proportion of the producers of each type to vary, i.e.

$P(\theta=\theta_1)=\alpha_1$ and $P(\theta=\theta_2)=\alpha_2$ with $\alpha_1+\alpha_2=1$. Let Q_0 denote the total expected additional units that the regulator needs.

Then the regulator's problem can be described as:

$$\min_{\{(q_1,T_1),(q_2,T_2)\}} TC \equiv \alpha_1 T_1 + \alpha_2 T_2 \qquad [4.6]$$

Subject to

$$T_1 \geq \theta_1 (q_1 - \tilde{q}) \qquad [4.7]$$

$$T_2 \geq \theta_2 q_2^2 \qquad [4.8]$$

$$\alpha_1 (q_1 - \tilde{q}) + \alpha_2 q_2 \geq Q_0 \qquad [4.9]$$

$$q_1 - \tilde{q} \geq 0, q_2 \geq 0 . \qquad [4.10]$$

Constraint [4.7] and [4.8] are participation constraints for the producers, implying that the cost of production needs to be at least fully compensated. Since there is no requirement that the regulator should pay more than the costs, these two constraints will be binding. Constraint [4.9] requires that the total quantity of offsets from all the producers be no less than Q_0 and it will also be binding.

Based on the Kuhn-Tucker conditions, the solution is given by

$$\frac{\partial C_1}{\partial q_1} = \frac{\partial C_2}{\partial q_2} \qquad [4.11]$$

$$\alpha_1 \left(q_1 - \tilde{q} \right) + \alpha_2 q_2 = Q_0 \qquad [4.12]$$

$$T_i = C_i, \ i = 1,2 . \qquad [4.13]$$

Full characterization of the solution is given in Appendix B. Production allocation among the Non-additional producers and the Additional producers is determined by equalization of marginal cost and then the non-additional amount is added to the contract for the non-additional producers. Because the regulator knows the type of each farmer, she is able to differentiate the contracts for different types. It follows that the total cost and the marginal cost of the program do not depend on the non-additional quantity $\tilde{\zeta}$.

2.2 The Screening Contract Method under Asymmetric Information

When the cost information is privately held by the producers and the regulator does not know who is who, it is not possible to offer differentiated contracts. She needs to design a uniform contract for the heterogeneous producers. In what follows, we investigate four alternative methods. In each section we first describe the alternative method, set up the corresponding regulator's problem and provide the solution. We then compare all the contracts using a numerical example.

2.2.1 Screening Contract with Price and Quantity Specifications

The regulator could specify a menu with two different combinations of production quantity and payment from which the producers can choose.

This contract method corresponds to the following problem for the regulator:

$$\min_{\{(q_1,T_1),(q_2,T_2)\}} TC \equiv \alpha_1 T_1 + \alpha_2 T_2 \qquad [4.14]$$

Subject to

$$T_1 \geq \theta_1(q_1 - \tilde{\zeta}) \qquad [4.15]$$

$$T_2 \geq \theta_2 q_2^2 \qquad [4.16]$$

$$\alpha_1(q_1 - \tilde{\zeta}) + \alpha_2 q_2 \geq Q_0 \qquad [4.17]$$

$$T_1 - \theta_1(q_1 - \tilde{\zeta}, \text{[illegible]} \tilde{\zeta}, \text{ if } q_2 > \tilde{\zeta};\ T_1 - \theta_1(q_1 - \tilde{\zeta}, \text{[illegible]}, \text{ otherwise} \quad [4.18]$$

$$T_2 - \theta_2 q_2^2 \geq T_1 - \theta_2 q_1^2 \quad [4.19]$$

$$q_1 - \tilde{\zeta} \text{[illegible]} 0 . \quad [4.20]$$

The interpretations of constraint [4.15] and [4.16] are straightforward—they are the participation constraints that require that the producers' costs are fully compensated. In the first best case, participation constraints of both types are binding. However, in this case since the regulator cannot observe which producers are of each type, constraint [4.15] will never be binding when $q_2 > 0$ as

$$T_2 - \theta_1(q_2 - \tilde{\zeta}, \text{[illegible]} \tilde{\zeta} \text{[illegible]} 0, \forall \theta_1 \leq \theta_2 . \quad [4.21]$$

Or in other words, any combination of quantity and payment designed for the Non-additional producers must offer him rents no less than that if he chooses the other combination designed for the Additional producers. This is the exact implication of constraints [4.18] and [4.19] – the incentive compatible constraints. Furthermore, equation [4.21] implies that, on one hand, the Non-additional producers can always guarantee some profits-- the so-called information rent—since they have the option of mimicking the less efficient Additional producers. On the other hand, there is no need to leave positive profits for the Additional producers. Therefore, the incentive compatible constraint [4.18] for the Non-additional producers will be binding and the participation constraint for the Additional producers (constraint [4.16]) will also be binding.

Based on the Kuhn-Tucker conditions, the production allocation between the types is given by

$$\frac{\partial C_1}{\partial q_1} = \left(1 + \frac{\alpha_1}{\alpha_2}\right)\frac{\partial C_2}{\partial q_2}, \text{ if } Q_0 \le \frac{\alpha_1\theta_2 + \alpha_2^2\theta_1}{\alpha_2\theta_1}\tilde{\zeta} \qquad [4.22]$$

$$\frac{\partial C_1}{\partial q_1} = (1 + \frac{\alpha_1}{\alpha_2}(1 - \frac{\theta_1}{\theta_2}))\frac{\partial C_2}{\partial q_2} + \frac{2\alpha_1\theta_1\tilde{\zeta}}{\alpha_2}, \text{ otherwise} \qquad [4.23]$$

$$\alpha_1\left(q_1 - \tilde{\zeta}\right) + \alpha_2 q_2 = Q_0 . \qquad [4.24]$$

T_1 and T_2 are given by constraint [4.16] and [4.18]. Full characterization of the solution is given in Appendix B.

Equations [4.22] and [4.23] suggest that it would always be optimal for the regulator to have the non-additional types produce some positive amount of additional production and pay them the production cost plus information rent. For the case in equation [4.22], the information rent is equal to the total production cost of the additional type. For the case in equation [4.23], the information rent is equal to the difference in the total production costs of producing q_2 between the two types. Furthermore, at the optimal production allocation the marginal cost of the Non-additional producers is greater than that of the Additional producers—i.e. the production from the Non-additional producers would be distorted upwards, i.e. $q_1^{SB} > q_1^*$, compared to the first-best case; and accordingly, production from the Additional producers would be distorted downwards, i.e. $q_2^{SB} < q_2^*$. This resembles the downward distortion of the production of the less efficient type in the principle-agent model, which is a result of the efficiency-information rent tradeoff (Laffont and Martimort 2002).

With regard to additionality, it is implied that some payment for the non-additional production is inevitable under asymmetric information. It is especially clear when the production of the Additional producers q_2^{SB} is less than the business as usual $\tilde{\zeta}$ of the Non-additional producers. In this case, the non-additional type can guarantee positive returns without doing anything.[32]

2.2.2 Screening Contract with Price Specifications Only

In our second possible contract design, the regulator specifies a schedule consisting of a unit payment plus a lump sum payment. Namely, the regulator specifies different unit payments for the environmental service provided, and the producers choose the unit payment they would like to receive and decides the quantity they would like to produce and at the end, the producers make a lump sum payment back to the regulator, the level of which depends on the unit payment. This is equivalent to the method of specifying a schedule of type-dependent unit payment and baseline. And it is exactly the method suggested in Mason and Plantinga (2010). Let t_i and S_i denote the unit charge and the

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[32] Note, if the assumption $a=\frac{\theta_2}{\theta_1}\geq 1$ fails, then the total cost of the Non-additional producers increases faster than that of the Additional producers. Therefore, the total cost of the Non-additional producers would intercept with that of the Additional producers at some production level. There are three possibilities of the allocation between the producers. The first possibility is that the optimal production quantities of both types are smaller than the production level at the intercept. In this case, the total cost of the Non-additional producers is smaller than that of the Additional producers. And the Non-additional producers would be the type that receives information rents. And the solution to the regulator's problem is similar to the solution with $a\geq 1$. The second possibility is that the optimal production quantity of the Non-additional producers (the Additional producers) is smaller (greater) than the production at the intercept. And the last possibility is that the optimal production quantities of both types are larger than the production level at the intercept. In these two cases, the Non-additional producers are not the type that receives information rents and therefore, no payment is made to the non-additional production.

In all, when the assumption $a=\frac{\theta_2}{\theta_1}\geq 1$ fails, the possibility that the Non-additional producers obtain information rents based on their non-additional production is limited by their fast-increasing costs.

lump sum payment for type i. Then the contract method corresponds to the following problem for the regulator:

$$\min_{\{(t_1,S_1),(t_2,S_2)\}} TC \equiv \alpha_1(q_1t_1 - S_1) + \alpha_2(q_2t_2 - S_2) \qquad [4.25]$$

Subject to

$$q_1t_1 - S_1 \geq \theta_1(q_1 - \tilde{\zeta} \text{ [illegible]} \qquad [4.26]$$

$$q_2t_2 - S_2 \geq \theta_2 q_2^2 \qquad [4.27]$$

$$\alpha_1(q_1 - \tilde{\zeta} \text{ [illegible]} \geq Q_0 \qquad [4.28]$$

$$q_1t_1 - S_1 - \theta_1(q_1 - \tilde{\zeta} \text{ [illegible]} \qquad [4.29]$$

$$q_2t_2 - S_2 - \theta_2 q_2^2 \geq q_2' t_1 - S_1 - \theta_2 {q_2'}^2 \qquad [4.30]$$

$$2\theta_1(q_1 - \tilde{\zeta} \text{ [illegible]} \qquad [4.31]$$

$$2\theta_2 q_2 = t_2 \qquad [4.32]$$

$$2\theta_1(q_1' - \tilde{\zeta} \text{ [illegible]} \qquad [4.33]$$

$$2\theta_2 q_2' = t_1 \qquad [4.34]$$

$$q_1 - \tilde{\zeta} \text{ [illegible]} \; \tilde{\zeta} \text{ [illegible]} \; 0, q_2' \geq 0. \qquad [4.35]$$

Equations [4.26] and [4.27] and equations [4.29] and [4.30] are the participation constraints and incentive compatibility constraints, respectively, similar to the ones in the method of screening contract with price and quantity specifications. As in that model, the participation constraint for the Additional producers [4.27] will bind, as will the incentive compatibility constraint for the Non-additional producers [4.29]. However, when the screening contract is specified in this way, there is no requirement that producers who choose the same unit charge produce the same quantity. Rather, each will choose its production to maximize its profit, so the production quantity is always set where marginal cost equals the unit payment (equations [4.31] through [4.34]).

Based on the Kuhn-Tucker conditions, the production allocation between the types is determined by

$$\frac{\partial C_1}{\partial q_1} = \left(1 + \frac{\alpha_1}{\alpha_2}\left(\frac{\theta_2}{\theta_1} - 1\right)\right)\frac{\partial C_2}{\partial q_2} + \frac{2\alpha_1\theta_2\tilde{\zeta}}{\alpha_2}\text{, if } Q_0 \geq \frac{\alpha_1^2\theta_2}{\alpha_2\theta_1}\tilde{\zeta} \qquad [4.36]$$

$$\frac{\partial C_1}{\partial q_1} = \frac{2\theta_1 Q_0}{\alpha_1}, \frac{\partial C_2}{\partial q_2} = 0 \text{ otherwise} \qquad [4.37]$$

$$\alpha_1\left(q_1 - \tilde{\zeta}\right) + \alpha_2 q_2 = Q_0\,. \qquad [4.38]$$

The whole problem can be solved based on the optimal production allocation, the binding constraints [4.27] and [4.29] and the production decision constraints [4.31] and [4.32]. If a baseline is specified instead of the lump sum payment that the producers need to pay back to the regulator, then the baseline for type i equals the lump sum payment S_i divided by the unit charge t_i. Full characterization of the solution is given in Appendix B.

2.3 The Non-discriminating Contracts

2.3.1 The Uniform Price Method

The uniform price method refers to a contract in which the regulator sets a unit price for all production and leaves the producers to decide their production quantities. The regulator determines the unit price by backward induction. For every unit price, the regulator will anticipate a certain amount of production from the producers so that the additional quantity can be anticipated. Finally the unit price is chosen to ensure that the target is reached.

This contract method corresponds to the following problem for the regulator:

$$\min_{t} TC \equiv \alpha_1 q_1 t + \alpha_2 q_2 t \qquad [4.39]$$

Subject to

$$2\theta_1(q_1 - \tilde{Q} \text{ [illegible]} \qquad [4.40]$$

$$2\theta_2 q_2 = t \qquad [4.41]$$

$$\alpha_1(q_1 - \tilde{Q} \text{ [illegible]} \, q_2 \geq Q_0 \,. \qquad [4.42]$$

Note that the number of variables at the regulator's disposal is reduced greatly from 4 in the screening contract method to 1 in this case. The decisions of the producers are nested in constraints [4.40] and [4.41] which follow from profit maximizing behavior. In this unit price method, production from all of the producers will be always non-zero as each unit of production will be paid a positive price while marginal costs start at zero and we assume there are no fixed costs. Production quantity is determined by equating marginal cost to marginal revenue.

Based on the Kuhn-Tucker conditions of the producers' problems, we know that

$$\frac{\partial C_1}{\partial q_1} = \frac{\partial C_2}{\partial q_2} = t \,, \qquad [4.43]$$

yielding equations [4.40] and [4.41]. In order for a contract to be accepted, the producer's revenue must exceed the production costs, i.e.

$$T_i = q_i * t = q_i * MC_{i|q=q_i} > \int_0^{q_i} MC_i(q)\,\mathrm{dq} \,. \qquad [4.44]$$

Since we assume that firms have no fixed costs, the participation constraint will not bind for either producer type.

Full characterization of the solution is given in Appendix B. The production allocation between the two types resembles the first-best case (equation [4.43]) but payments to the producers (and therefore cost of the program) would be larger (equation [4.44]). In addition to producer surplus paid to the additional units, the Non-additional producers get extra surplus because the same unit price is also paid to the non-additional units (Area I in figure 4.3).

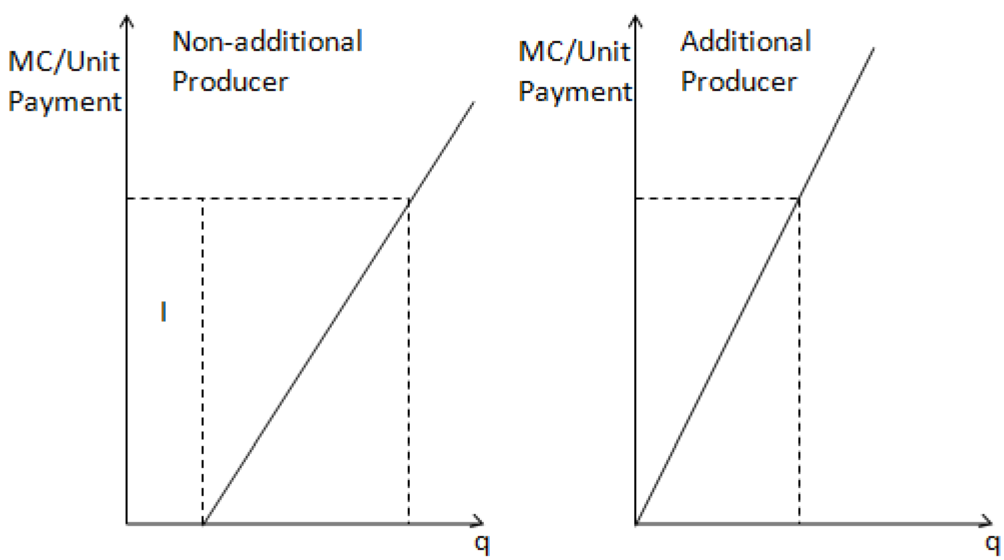

Figure 4.3: Payments to the Producers under the Uniform Price Method

2.3.2 The Baseline Method

To avoid paying for the non-additional units, a common approach is for the regulator to announce a “baseline” and only pay for the part of production great than the baseline. However, in our setting, since the regulator does not know who has non-additional production, this has to be applied uniformly. We refer this to the “baseline” contract.

This contract method corresponds to the following problem for the regulator:

$$\min_{(\hat{Q},t)} TC \equiv \alpha_1\left(q_1-\hat{Q}\right)t+\alpha_2\left(q_2-\hat{Q}\right)t \qquad [4.45]$$

Subject to

$$2\theta_1\left(q_1-\tilde{Q}\right. \text{[illegible]} \text{ if } \left(q_1-\hat{Q}\right)t \ge \theta_1\left(q_1-\tilde{Q}\right. \text{[illegible]} \; ; q_1=\tilde{Q}, \text{ otherwise} \qquad [4.46]$$

$$2\theta_2 q_2 = t \text{ if } \left(q_2-\hat{Q}\right)t \ge \theta_2 q_2^2 \; ; q_2=0, \text{ otherwise} \qquad [4.47]$$

$$\alpha_1\left(q_1-\tilde{Q}\right. \text{[illegible]} \ge Q_0 \qquad [4.48]$$

Now, the contract offered to the producers contains two variables: the baseline $\hat{Q}$ and the unit price *t*. The uniform price contract can be regarded as a degeneration of the baseline method where the baseline is set to equal 0.

On the producer side, constraints [4.46] and [4.47] represent the decisions of the producers. Again, the producers have two decisions to make: whether to produce and how much to produce. It is easier to solve for these two decisions backwards than forwards. The quantity to produce depends only on the unit payment, which is simply a re-arrangement of the equation representing the equalization of marginal cost and marginal benefit. Furthermore, when both types are active in the program, the production allocation between the two types again follows $\frac{\partial C_1}{\partial q_1}=\frac{\partial C_2}{\partial q_2}=t$. The baseline, on the other hand, only affects the producers' decision on whether to produce but not the production quantity. Substituting the unit payment t in the inequalities in equations [4.46] and [4.47] with q_i, it follows that the highest level of baseline that keeps the producers from exiting production would be $\frac{t}{4\theta_i}+\tilde{\zeta}_i$, implying that the producers would always accept a baseline that is slightly higher than their individual business as usual.

Although the business as usual $\tilde{\zeta}$ seems to be a natural candidate for the baseline; it does not necessarily minimize the total cost. In the next two sections we first examine the case where $\hat{Q}=\tilde{\zeta}$ and then examine the situation where the regulator strategically chooses $\hat{Q}$ to minimize total cost.

2.3.2.1 Take the Business As Usual As Baseline $\hat{Q}=\tilde{\zeta}$

For the Non-additional producers, setting $\hat{Q}=\tilde{\zeta}$ ensures that only additional production is paid. Therefore, for given unit price t, $q_1=\frac{t}{2\theta_1}+\tilde{\zeta}$ and this leaves them profit

$\left(q_1-\tilde{\zeta}\right.$ [illegible] $\frac{{}^2}{4\theta_1}$. For the Additional producers, however, the cost of producing the baseline amount becomes a fixed cost, and they will only participate when the unit price is high enough that the fixed cost is fully compensated. Replacing the $\hat{Q}$ in constraint [4.47] with $\tilde{\zeta}$, it can be derived from that the break-even price for the Additional producers is $t=4\theta_2\tilde{\zeta}$. And producers will earn profit when $t>4\theta_2\tilde{\zeta}$.

The solution depends on the relation between the baseline $\tilde{\zeta}$ and the expected production Q_0. When Q_0 is small relative to $\tilde{\zeta}$ (namely, $Q_0 < \frac{2\alpha_1\theta_2}{\theta_1}\tilde{\zeta}$), there is no need to set the unit payment to be greater than the break-even price of the Additional producers. By setting the unit payment equal to $\frac{2\theta_1 Q_0}{\alpha_1}$, the regulator reaches its target Q_0 by procuring from the Non-additional producers only. The additional producers will be left out of the program.

When Q_0 is large ($Q_0 \geq \frac{2\alpha_1\theta_2}{\theta_1}\tilde{\zeta}$), the unit payment *t* will be large enough to induce production from both types. When *t* is exactly equal to $4\theta_2\tilde{\zeta}$, the Additional producers is indifferent between to participate the program and not to participate but each of them have to sell $2\tilde{\zeta}$ so that their cost would be fully compensated. And the regulator is able to buy $Q_0 = \frac{2(\alpha_1\theta_2 + \alpha_2\theta_1)\tilde{\zeta}}{\theta_1}$ at the maximum without increasing the unit payment *t*. To find out the market equilibrium and the total payment of the program for this small range of target, we need to add an ancillary assumption that not every additional producer would participate. As Q_0 continues to increase to be greater than $\frac{2(\alpha_1\theta_2 + \alpha_2\theta_1)\tilde{\zeta}}{\theta_1}$, the target constraint will bind again and to induce additional environmental service production to reach the desired level the unit payment *t* needs be greater than the break-even price for the Non-additional producers. The production allocation is again determined by equalization of marginal cost of the two types. But the regulator pays less to the producer than that in the uniform price case.

$$\frac{\partial C_1}{\partial q_1} = \frac{\partial C_2}{\partial q_2} \qquad [4.49]$$

$\alpha_1 \left(q_1 - \tilde{\zeta} \right)$ [illegible] $_2 q_2 = Q_0$ [4.50]

$T_i = (q_i - \tilde{\zeta}$ [illegible] $_{i|q=q_i}$ [4.51]

Full characterization of the solution is presented in Appendix B.

2.3.2.2 When the Baseline is Determined by Cost Minimization (Optimal Baseline)

Consider the situation in the previous section. Whoever is producing, earns positive profits. It is tempting for the regulator to raise the baseline as long as the increase of baseline does not cause the producers to exit production. By so doing the regulator can procure the same amount of production but reduce payments.

On one hand, for any given $\hat{Q}$, q_1, q_2 and t can be solved from constraints [4.46] through [4.48] which constitute a system of just-identified equations. On the other hand, $\frac{\partial TC}{\partial \hat{Q}} = -t < 0$ meaning that total cost decreases with higher baseline *ceteris paribus*. Together, they imply that under given unit price t, the regulator can continue to raise the baseline without increasing t as long as it does not change the participation decisions of the producers.

But one question remains for the regulator: whether to have one type or both types to produce. Figure 4.4 demonstrates the situation. In the figure we assume that by setting the unit price at t_1, the regulator induces additional production quantities equal to

OE and OB from the Non-additional producers and Additional producers respectively, which sum to Q_0. In this case, the cost-minimizing baseline would be OA=OB/2 which leaves zero profit for the Additional producers and profit for the Non-additional producers equals the area of AGIC. Total cost of the program equals $\alpha_1 * S(AGHB) + \alpha_2 * S(AGIE)$, where S(•) represents the area of the rectangle.

On the other hand, it is also possible to obtain Q_0 from the Non-additional types alone. In this case the regulator would set the baseline higher but the cost of production would be higher since it excludes the low-cost production from the Additional producers. It can be solved that q_1=OF, q_2=0 and $t=t_2$ and the baseline would be OD=OC+(OF-OC)/2=OF/2+OC/2 which leaves zero profit for both types of producers. The regulator's total cost equals $\alpha_1 * S(DJKF)$. Which way has a lower cost to the regulator is not clear. In our two-type model, the problem can be solved analytically. The full characterization of solutions under both situations is shown in table 4.1.

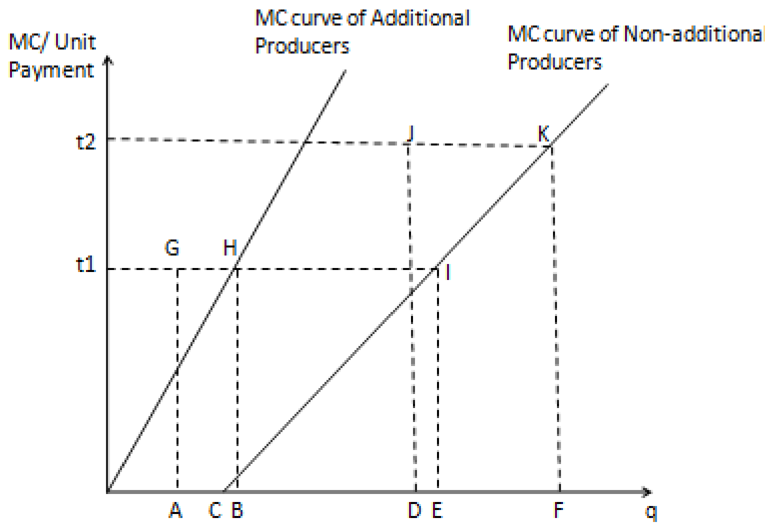

Figure 4.4: Illustration of Total Costs in the Optimal Baseline Case

Table 4.1: Characterization of Solution in the Optimal Baseline Case

	Unit Payment t	**Production of Non-additional Producers** q_1	**Production of Additional Producers** q_2	**Optimal Baseline** $\hat{Q}$	**Total Cost to Regulator** TC
BA_both	$\dfrac{Q_0}{\dfrac{\alpha_1}{2\theta_1}+\dfrac{\alpha_2}{2\theta_2}}$	$\dfrac{\theta_2 Q_0}{\theta_2\alpha_1+\theta_1\alpha_2}+\tilde{\zeta}$	$\dfrac{\theta_1 Q_0}{\theta_2\alpha_1+\theta_1\alpha_2}$	$\dfrac{\theta_1 Q_0}{2\theta_2\alpha_1+2\theta_1\alpha_2}$	$\dfrac{\theta_1\theta_2[(2\theta_2-\theta_1)\alpha_1+\theta_1\alpha_2]Q_0^2}{(\theta_2\alpha_1+\theta_1\alpha_2)^2}+\dfrac{2\alpha_1\theta_1\theta_2 Q_0\tilde{\zeta}}{\theta_2\alpha_1+\theta_1\alpha_2}$
BA_low	$\dfrac{2\theta_1 Q_0}{\alpha_1}$	$\dfrac{Q_0}{\alpha_1}+\tilde{\zeta}$	0	$\dfrac{Q_0}{2\alpha_1}+\tilde{\zeta}$	$\dfrac{\theta_1}{\alpha_1}Q_0^2$
Note: BA_both refers to the situation in which Q_0 is produced by both types and BA_low refers to the situation in which Q_0 is produced by the Non-additional producers only.					

The most interesting points in table 4.1 lie in the last two columns. First, when the target Q_0 is small it is always better to leave the additional type producers out of the program. As Q_0 increases, the optimal strategy will switch to setting a low-baseline to include the additional type at some point if $\frac{2\theta_1}{\alpha_1} > \frac{2\theta_1\theta_2[(2\theta_2-\theta_1)\alpha_1+\theta_1\alpha_2]}{(\theta_2\alpha_1+\theta_1\alpha_2)^2}$ (i.e. $\frac{\theta_2}{\theta_1} < \frac{2-\alpha_1}{\alpha_1}$) (Proof in Appendix C.1). Second, the optimal baseline is linearly increasing in the target Q_0 under both cases. Especially, when both types are producing, the optimal baseline does not depend on the additionality parameter at all. It is possible that the baseline falls below the business as usual $\tilde{\zeta}$ when the optimal baseline suddenly drops as the optimal strategy switches from being open to one type to being open to both types and then the optimal baseline continues to increase with Q_0 and will pass $\tilde{\zeta}$ again.

3. Comparison of Different Designs

3.1 General Results

Solving the problems corresponding to different policy designs leads us to the following results:

1) The ranking of designs based on total cost to the regulator (from lowest total cost to highest) is as follows:

- the screening-contract method with price and quantity specifications,
- the screening-contract method with price specification only,
- the optimal baseline method,
- the business as usual baseline method,
- the uniform price method.

When both the target and the proportion of non-additional producers are small, the uniform price method may be a good choice for its total cost could be much lower than the business as usual baseline method and close to the optimal baseline method. This is demonstrated in the left panel of figures 4.5 and 4.6 where a numerical example is provided demonstrating how the total costs to the regulator of different designs change with changes in the proportion of the non-additional producers, α_1, and the target level of production, Q_0, respectively. Analytical rankings of the different policies are derived in Appendix C.2.

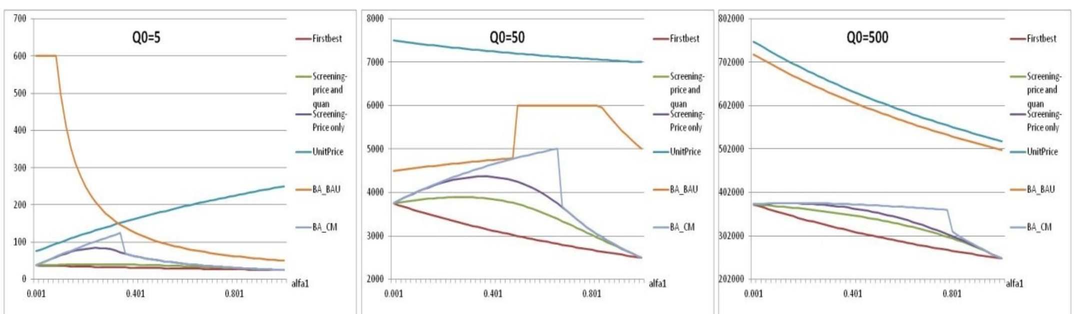

Figure 4.5: Total Costs of Alternative Designs for Different Values of α_1 (Business as Usual $\tilde{\zeta}$ =20, a=1.5)

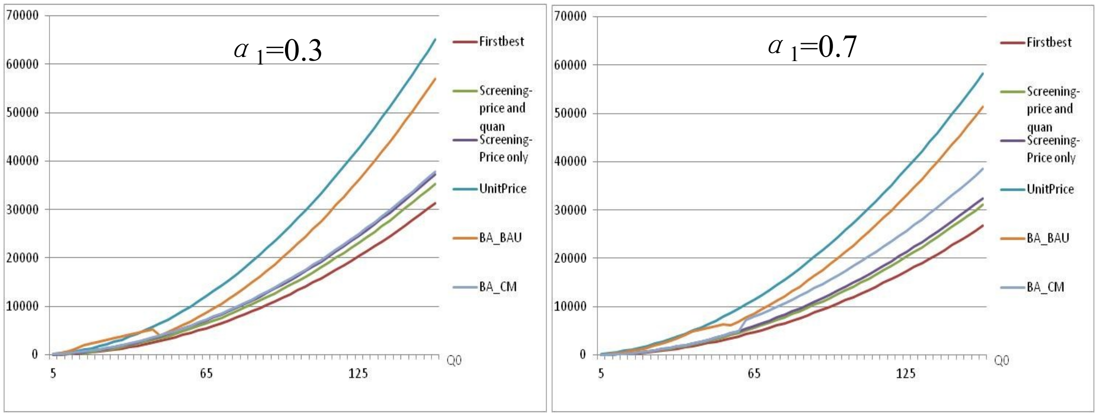

Figure 4.6: Total Costs of Alternative Designs for Various Targets (Business as Usual $\tilde{\zeta}$ =20, *a*=1.5)

2) As seen in figure 4.7, the ratios of the total costs of the methods discussed relative to the total cost in the first best case converge to certain values as the target approaches positive infinity. For the screening-contract methods and the baseline-optimal, the values of the convergence depend on the difference in the marginal costs of the producers, *a*. When the marginal cost curves of different type producers are only different in their locations but not in their slopes, i.e. *a*=1, the total costs of the screening contract methods and the baseline-optimal method relative that of the first best case converge to 1.

The ratios of the total costs of the uniform price method and the baseline_business as usual method relative to the total cost of the first-best case converge to 2 regardless of the values of cost differences and the distribution of the two types.

Analytical solution is derived in Appendix C.3.

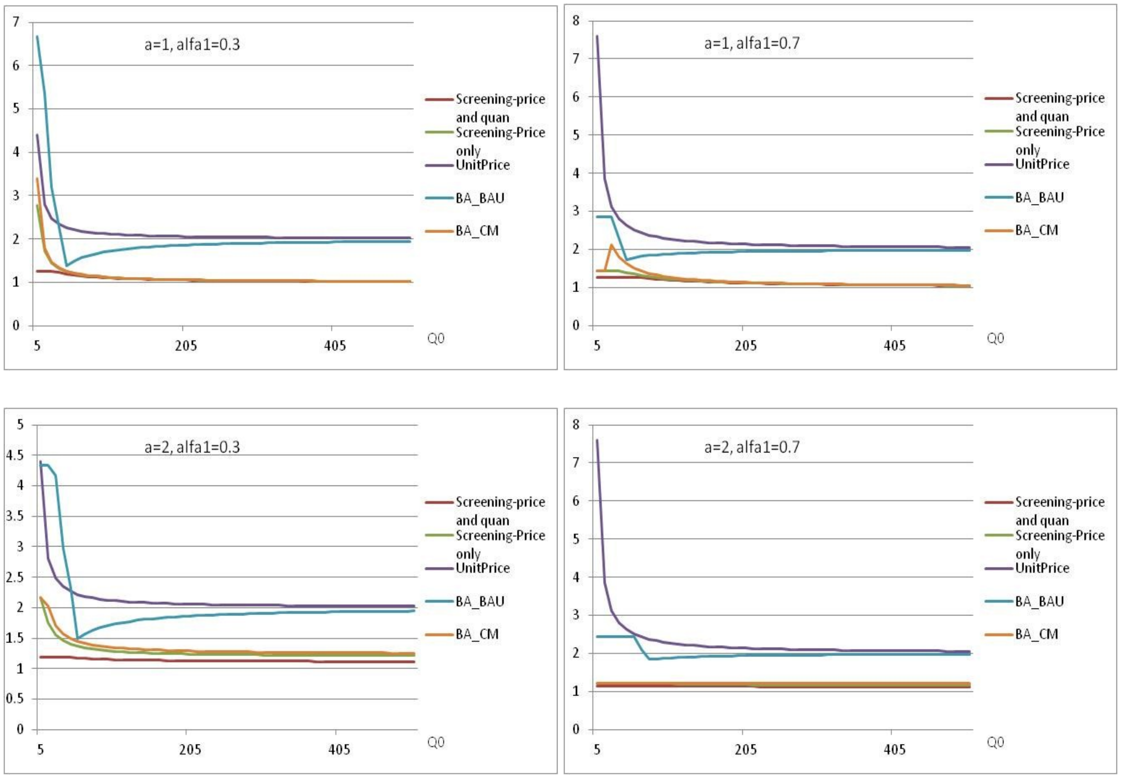

Figure 4.7: Total Costs of Alternative Designs Relative to the First-Best Case (Business as Usual $\tilde{\zeta}$ =20)

3) As seen in figure 4.8, as the proportion of either type becomes larger, there is a tendency for the total cost of the second-best screening contract to converge to that of the first-best case. Furthermore, the total cost of the optimal baseline method converges to that of the second-best case (and therefore also the first-best case). This is because as the group of producers becomes less heterogeneous, the regulator pays less information rents and the outcome approaches closer to the first-best case.

The analytical is derived in Appendix C.4.

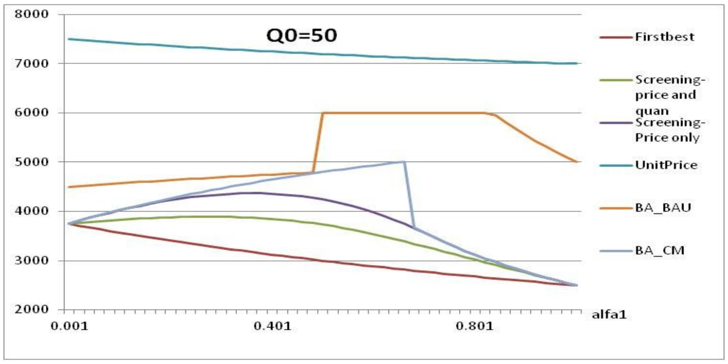

Figure 4.8: Total Costs of Alternative Designs for Different Proportions of the Non-additional Producers ($\tilde{\zeta}$ =20, a=1.5)

4) As total cost and therefore marginal cost of procuring given amount of environmental service depend on the contract design used in the procurement, different methods used would very likely imply different social optimal levels of environmental service. This is certain when the marginal benefits do not depend on the payment, which holds for many environmental services. Figure 4.9 demonstrates this pattern using a numerical example. We see that the marginal cost to the regulator is always lowest with the first-best contract. However, presuming that that policy is not available, the regulator should choose the policy which achieves the lowest cost and that may vary depending on the size of the target. Moreover, if the regulator represents the public that benefits from the acquisition of production, the optimal level of production would be where the marginal benefit to the public equals the marginal cost to the regulator. Hence, the optimal value for $\tilde{\zeta}$ will vary depending on which designs is available to the regulator.

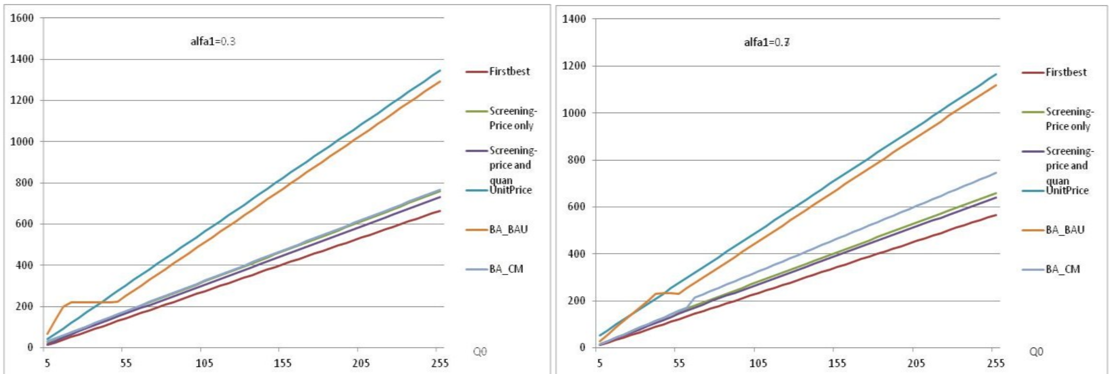

Figure 4.9: Marginal Costs of Alternative Designs against the Target (Business as Usual $\tilde{\zeta}$=20, a=1.5)

4. Model Extension

In Appendix D we extend our analysis to a more general case in which there is a continuous distribution case of producer types, each with a different level of business as usual production. For analytical convenience we assume that the producers share the same slope of the marginal cost curves but their business as usual production $\tilde{\zeta}$ follows a distribution over the interval $[0,\bar{\theta}]$. Namely, the total cost curve of the producers can be represented as equation [4.52]:

$$TC(\theta) = \beta(q-\theta)^2 \text{, where } \theta \text{ is uniformly distributed between } [0,\bar{\theta}]. \quad [4.52]$$

And therefore, the marginal cost curve would be:

$$MC(\theta) = 2\beta(q-\theta)q. \quad [4.53]$$

As shown in the appendix, the first-best, second-best cases and uniform price method are formulated by replacing the summation over α_1 and α_2 with the integral over the distribution. Results regarding the cost-effectiveness and the convergence of the ratios of the total costs of different designs relative to that of the first best case still hold.

5. Limitations and Conclusion

Additionality is one of the major concerns in designing efficient Payments for Environmental Service programs. In this paper, we have investigated four contract designs of these programs, including two variants of discriminating method, the baseline method and the uniform method in the situation in which the service buyer knows the existence but not the specific sources of the non-additional services and aims to minimize the costs of procuring given amount of additional environmental services.

The limitations of our study come in the following regards. Firstly, the assumption on the knowledge of the regulator is quite strong. In practice, it may be very costly or impossible for her to develop knowledge on the cost parameters of the individual producers and the associated distribution. Furthermore, our model is rather abstract. The lack of empirical and institutional context means that substantial work needs to be done before the idea could be used in practice. In spite of these limitations, our model has led to some interesting findings.

We find that the screening contract method is the most cost-effective, especially when the buyer specifies a schedule of combinations of production quantity and total payment, which agrees with the general regulation literature. The existence of non-additional environmental service opens up new policy design possibility, i.e. the baseline method in which the service buyer specifies a baseline and makes payments to services above the baseline only. We find that when the baseline is determined by program cost minimization, the cost of the baseline method is only slightly higher than the screening contract method. Furthermore, the optimal baseline increases with the procurement target. In other words, when the target is large enough, the optimal baseline would be larger than the non-additional production of any producer. On the other hand, if the baseline is rigidly set (for example at the business as usual level), the cost of the baseline method could be greater than that of the uniform price method in which the service buyer simply sets a price to buy all the environmental service produced.

CHAPTER V

CONCLUSIONS

1. Major Findings

Climate change presents a great challenge to scientists, policy makers and the global society. This dissertation focuses on the issues of leakage and additionality in realizing the climate change mitigation opportunities in the agricultural sector.

The first two essays of this dissertation (Chapter II and Chapter III) are devoted to development of a global partial equilibrium agricultural sector model with a detailed US component. And in the second essay, the model is applied to analyze implications of technological progress in US crop yield growth on the international effects of US bioenergy policy based on new econometric estimates of the trends in US crop yield growth rates over the past 70 years. Slowdowns in the 1960s and 1970s are found to be significant and prevalent in US crop yield growth rates. The importance of the assumptions regarding technological progress is exhibited in our analysis of the Renewable Fuel Standard (RFS), which is our reference bioenergy policy. It is found that the RFS policy, on the producer's side, diverts land to plantations of bioenergy feedstock crops from other crops and, on the consumer's side, diverts crop usage to bioenergy production to from other purposes. These effects are significant in the short-term if crop yields grow at their current rates. In the medium term, technology progress would play a bigger role in determining crop production. However, in terms of welfare and leakage, the RFS tends to have larger impacts than technological progress over the whole simulation period. Our model predicts that if US crops grow at the current rate, the implementation of RFS policy would cause an addition of 1.16 million hectares of agricultural land expansion in rest of the world, which comes from deforestation and loss of natural land. Although there is great uncertainty in this quantitative result, which is inherent in making future predictions, our research offers several important messages. A slowing in crop yield growth rates would lead to large increases in clearance of forest and natural land while higher technological progress would mitigate the leakage effect of the RFS policy. Whether the leakage effect can be completely offset depends on the mix of yield growth of all crops. Furthermore, specific regions could incur larger loss of forest land and/or natural land in scenarios with higher crop yield growth rates.

The third essay (Chapter IV) is devoted to investigate the additionality problem in designing Payments for Environmental Service programs. Four contract designs of these programs are investigated in the situation in which the service buyer knows the existence but not the specific sources of the non-additional services and aims to minimize the costs of procuring given amount of additional environmental services. The key finding is that the existence of non-additional environmental service opens up new policy design possibilities. Of particular interest is the baseline method in which the service buyer specifies a baseline and makes payments to services above the baseline only. And when the baseline is set to minimize costs, the cost is only slightly higher than the second-best screening contract method. Furthermore, a cost minimizing baseline would generally deviate from the non-additional production (the so-called business-as-usual level) of the producers and increase with the procurement target.

2. Possible Future Works

The modeling exercise in the dissertation is an attempt to make better assessment of the leakage effect in increasing the role of the agricultural sector in climate change mitigation. Our sensitive analysis shows that there are at least two aspects of which the model can be further improved: 1) the trade component is not very well calibrated, which is an important factor in determining the special distribution of the leakage effect; 2) the one period ahead simulation suggests the demand growth parameters in the model is very possibly smaller than the actual value. This would result in underestimation of the leakage effect, provided that land with high productivity is first converted for production.

We further examine the relationship between technological progress and leakage. This analysis not only highlights the important of technological progress but also reveals that the mix of progress in different crops also matter in determining the leakage effect. Future work could extend the analysis to model yield growth with the production function approach so as to offer better understanding on the sources of yield growth.

Additionality is another barrier in realizing the climate change mitigation opportunities in the agricultural sector. The last essay offers interesting insights in achieving additionality in policy design. Directions of future work include, for example, to extend the analysis to real world programs or to develop empirical models to test the theoretical findings.

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APPENDIX A

Soybean-Estimation						
Model	Estimation Result	Break Year	Ljung-Box Test (5% Confidence)	Implied Growth Rate		SSE/MSE
				Beginning of the Period	End of the Period	
Simple Linear Model – No break point	a=-681.95 b=0.36	--	Fail to Reject	2.22%	0.81%	SSE=335.66 MSE=4.94
Simple Exponential Model –No break point	a=-23.41 b=0.013	--	Fail to Reject	1.28%	1.28%	SSE=293.04 MSE=4.31
Model 1 (Exponential + Linear-unrestricted)	a_1=-70.51 b_1=0.038	1979	Reject	3.80%	3.80%	SSE=279.20 MSE=4.23
	a_2=-960.27 b_2=0.50		Fail to Reject	1.89%	1.13%	
Model 2 (Exponential + Exponential-unrestricted)	a_1=-20.45 b_1=0.012	1988	Reject	1.20%	1.20%	SSE=285.47 MSE=4.33
	a_2=-18.58 b_2=0.011		Fail to Reject	1.10%	1.10%	
Model 3 (Linear + Exponential -unrestricted)	a_1=-560.92 b_1=0.30	1988	Reject	1.85%	0.93%	SSE=278.04 MSE=4.21
	a_2=-18.58 b_2=0.011		Fail to Reject	1.10%	1.10%	
Model 4 (Linear + Linear-unrestricted)	a_1=-560.92 b_1=0.30	1988	Reject	1.85%	0.93%	SSE=277.82 MSE=4.21
	a_2=-812.52 b_2=0.43		Fail to Reject	1.62%	0.98%	
Model 5 (Exponential + Linear-restricted)	a_1=-21.00 b_1=0.012	1984	Reject	1.20%	1.20%	SSE=289.92 MSE=4.33
	a_2=-904.00 b_2=0.47		Fail to Reject	1.38%	1.06%	
Model 6 (Exponential + Exponential -restricted)	a_1=-24.36 b_1=0.014	1959	Fail to Reject	1.40%	1.40%	SSE=291.98 MSE=4.36
	a_2=-21.39 b_2=0.013		Reject	1.30%	1.30%	
Model 7 (Linear + Exponential-restricted)	a_1=-577.87 b_1=0.31	1983	Fail to Reject	1.91%	1.18%	SSE=289.31 MSE=4.32
	a_2=-23.41 b_2=0.014		Reject	1.40%	1.40%	
Model 8 (Linear + Linear-restricted)	a_1=-565.43 b_1=0.3	1983	Fail to Reject	1.85%	1.15%	SSE=284.65 MSE=4.25
	a_2= -932.29 b_2=0.49		Fail to Reject	1.74%	1.11%	

Soybean-Validation					
Model	Estimation Result-0	Estimation Result-5	Out of sample Prediction Error-5	Estimation Result-10	Out of sample Prediction Error-10
Simple Exponential Model-No break point	SSE=293.04 MSE=4.31 a=-23.41 b=0.014	SSE=276.82 MSE=4.39 a=-21.57, b=0.013	16.64	SSE=234.96 MSE=4.05 a=-22.26, b=0.013	60.78
Model 3 (Linear + Exponential-unrestricted)	SSE=278.04 MSE=4.21 Year=1988	SSE=259.30 MSE=4.25 Year=1988	27.08	SSE=217.58 MSE=3.89 Year=1979	150.18
	a_1=-560.92 b_1=0.30	a_1=-560.92 b_1=0.30		a_1=-593.67 b_1=0.32	
	a_2=-18.58 b_2=0.011	a_2=-14.54 b_2=0.09		a_2=-31.20 b_2=0.017	
Model 4 (Linear + Linear-unrestricted)	SSE=277.82 MSE=4.21 Year=1988	SSE=258.63 MSE=4.24 Year=1988	28.21	SSE=215.73 MSE=3.85 Year=1982	122.57
	a_1=-560.92 b_1=0.30	a_1=-560.92 b_1=0.30		a_1=-582.19 b_1=0.31	
	a_2=-812.52 b_2=0.43	a_2=-645.08 b_2=0.34		a_2=-1244.29 b_2=0.64	
Model 8 (Linear + Linear-restricted)	SSE=284.65 MSE=4.25 Year=1983	SSE=268.88 MSE=4.34 Year=1983	16.62	SSE=221.94 MSE=3.89 Year=1988	141.07
	a_1=-565.43 b_1=0.3	a_1=-568.53 b_1=0.30		a_1=-575.16 b_1=0.31	
	a_2= -932.29 b_2=0.49	a_2=-904.53 b_2=0.47		a_2=-1329.56 b_2=0.69	

Wheat-Estimation

Model	Estimation Result	Break Year	Ljung-Box Test	Implied Growth Rate		SSE/MSE
				Beginning of the Period	End of the Period	
Simple Linear Model –No break point	a=-815.60 b=0.43	--	Reject	2.81%	0.97%	SSE=441.68 MSE=6.50
Simple Exponential Model –No break point	a=-23.63 b=0.014	--	Reject	1.40%	1.40%	SSE=640.93 MSE=9.43
Model 1 (Exponential + Linear-unrestricted)	a_1=-36.89 b_1=0.020	1985	Reject	2.0%	2.0%	SSE=342.36 MSE=5.19
	a_2=-699.12 b_2=0.37		Fail to Reject	1.07%	0.84%	
Model 2 (Exponential + Exponential-unrestricted)	a_1=-36.89 b_1=0.020	1985	Reject	2.00%	2.00%	SSE=342.98 MSE=5.20
	a_2=-15.11 b_2=0.009		Fail to Reject	0.90%	0.90%	
Model 3 (Linear + Exponential-unrestricted)	a_1=-982.27 b_1=0.51	1985	Reject	3.33%	1.36%	SSE=359.53 MSE=5.45
	a_2=-15.11 b_2=0.009		Fail to Reject	0.90%	0.90%	
Model 4 (Linear + Linear-unrestricted)	a_1=-982.27 b_1=0.51	1985	Reject	3.33%	1.36%	SSE=358.90 MSE=5.44
	a_2=-699.12 b_2=0.37		Fail to Reject	1.07%	0.84%	
Model 5 (Exponential + Linear-restricted)	a_1=-51.77 b_1=0.028	1959	Fail to Reject	2.80%	2.80%	SSE=407.69 MSE=6.08
	a_2=-754.65 b_2=0.40		Fail to Reject	1.53%	0.90%	
Model 6 (Exponential + Exponential -restricted)	a_1=-44.70 b_1=0.023	1972	Fail to Reject	2.30%	0.90%	SSE=355.78 MSE=5.31
	a_2=-14.37 b_2=0.009		Fail to Reject	2.30%	0.90%	
Model 7 (Linear + Exponential-restricted)	a_1=-950.71 b_1=0.50	1983	Reject	3.27%	1.27%	SSE=373.45 MSE=5.57
	a_2=-11.20 b_2=0.007		Fail to Reject	0.70%	0.70%	
Model 8 (Linear + Linear-restricted)	a_1=-948.72 b_1=0.50	1983	Reject	3.27%	1.27%	SSE=375.09 MSE=5.60
	a_2=-530.31 b_2=0.29		Fail to Reject	0.75%	0.65%	

Wheat-Validation

Model	Estimation Result-0	Estimation Result-5	Out of sample Prediction Error-5	Estimation Result-10	Out of sample Prediction Error-10
Simple Linear Model-No break point	SSE=441.68 MSE=6.50 a=-815.60 b=0.43	SSE=394.95 MSE=6.27 a=-844.12, b=0.44	55.18	SSE=330.43 MSE=5.69 a=-870.54, b=0.46	143.70
Model 1 (Exponential + Linear-unrestricted)	SSE=342.36 MSE=5.19 Year=1985	SSE=315.61 MSE=5.17 Year=1985	32.36	SSE=263.37 MSE=4.70 Year=1985	121.65
	a_1=-36.89 b_1=0.020	a_1=-36.89 b_1=0.020		a_1=-36.89 b_1=0.020	
	a_2=-699.12 b_2=0.37	a_2=-507.18 b_2=0.42		a_2=-980.62 b_2=0.511	
Model 2 (Exponential + Exponential-unrestricted)	SSE=342.98 MSE=5.20 Year=1985	SSE=315.52 MSE=5.17 Year=1985	36.03	SSE=262.29 MSE=4.68 Year=1985	155.46
	a_1=-36.89 b_1=0.020	a_1=-36.89 b_1=0.020		a_1=-36.89 b_1=0.020	
	a_2=-15.11 b_2=0.009	a_2=-18.38 b_2=0.011		a_2=-24.01 b_2=0.014	
Model 6 (Exponential + Exponential-restricted)	SSE=355.78 MSE=5.31 Year=1972	SSE=328.56 MSE=5.29 Year=1971	30.87	SSE=277.59 MSE=4.87 Year=1971	91.43
	a_1=-44.70 b_1=0.023	a_1=-44.14 b_1=0.024		a_1=-43.75 b_1=0.024	
	a_2=-14.37 b_2=0.009	a_2=-15.38 b_2=0.010		a_2=-16.22 b_2=0.010	

Cotton-Estimation

Model	Estimation Result	Break Year	Ljung-Box Test	Implied Growth Rate: Beginning of the Period	Implied Growth Rate: End of the Period	SSE/MSE
Simple Linear Model –No break point	a=-14928.76 b=7.82	--	Reject	3.09%	1.00%	SSE=228540.84 MSE=3360.89
Simple Exponential Model –No break point	a=-23.87 b=0.015	--	Reject	1.50%	1.50%	SSE=240504.77 MSE=3536.83
Model 1 (Exponential + Linear-unrestricted)	a_1=-53.94 b_1=0.030	1968	Reject	3.00%	3.00%	SSE=174773.25 MSE=2648.08
	a_2=-18361.00 b_2=9.54		Fail to Reject	2.20%	1.22%	
Model 2 (Exponential + Exponential-unrestricted)	a_1=-63.60 b_1=0.034	1965	Reject	3.40%	3.40%	SSE=166730.98 MSE=2526.23
	a_2=-23.32 b_2=0.015		Fail to Reject	1.50%	1.50%	
Model 3 (Linear + Exponential-unrestricted)	a_1=-21473.04 b_1=11.18	1968	Reject	4.42%	2.17%	SSE=172089.35 MSE=2607.414
	a_2=-24.80 b_2=0.016		Reject	1.60%	1.60%	
Model 4 (Linear + Linear-unrestricted)	a_1=-21473.04 b_1=11.18	1968	Reject	4.42%	2.17%	SSE=175296.40 MSE=2656.01
	a_2=-18361.00 b_2=9.54		Fail to Reject	2.20%	1.23%	
Model 5 (Exponential + Linear-restricted)	a_1=-53.82 b_1=0.031	1959	Reject	3.10%	3.10%	SSE=221114.51 MSE=3300.22
	a_2=-13875.67 b_2=7.29		Reject	1.63%	0.94%	
Model 6 (Exponential + Exponential-restricted)	a_1=-58.04 b_1=0.033	1959	Reject	3.30%	3.30%	SSE=196029.15 MSE=2925.81
	a_2=-19.56 b_2=0.013		Reject	1.30%	1.30%	
Model 7 (Linear + Exponential-restricted)	a_1=-19180.01 b_1=10.00	1959	Reject	3.95%	2.17%	SSE=200398.61 MSE=2991.02
	a_2=-20.28 b_2=0.013		Reject	1.30%	1.30%	
Model 8 (Linear + Linear-restricted)	a_1=-13331.57 b_1=7.00	1980	Reject	2.77%	1.73%	SSE=221025.06 MSE=3298.88
	a_2=-17546.99 b_2=9.13		Fail to Reject	1.68%	1.18%	

Cotton-Validation

Model	Estimation Result-0	Estimation Result-5	Out of sample Prediction Error-5	Estimation Result-10	Out of sample Prediction Error-10
Simple Linear Model-No break point	SSE=228540.84 MSE=3360.89 a=-14928.76 b=7.82	SSE=198040.33 MSE=3143.49 a=-14070.00, b=7.38	38155.61	SSE=174449.327 MSE=3007.74 a=-13856.30, b=7.27	65988.49
Model 2 (Exponential + Exponential-unrestricted)	SSE=166730.98 MSE=2526.23 Year=1965	SSE= 149416.60 MSE= 2449.45 Year=1965	23595.45	SSE=128365.87 MSE=2292.24 Year=1965	47840.58
	a_1=-63.60 b_1=0.034	a_1=-63.60 b_1=0.034		a_1=-63.60 b_1=0.034	
	a_2=-23.32 b_2=0.015	a_2=-20.90 b_2=0.014		a_2=-20.27 b_2=0.013	
Model 3 (Linear + Exponential-unrestricted)	SSE=172089.35 MSE=2607.414 Year=1968	SSE= 175970.26 MSE= 2838.23 Year=1960	34794.09	SSE= 152525.86 MSE= 2675.89 Year=1960	70560.15
	a_1=-21473.04 b_1=11.18	a_1= -20673.55 b_1= 10.76		a_1= -21247.65 b_1= 11.06	
	a_2=-24.80 b_2=0.016	a_2= -17.40 b_2= 0.012		a_2= -16.21 b_2= 0.011	
Model 6 (Exponential + Exponential-restricted)	SSE=196029.15 MSE=2925.81 Year=1959	SSE=170609.23 MSE=2751.76 Year=1959	36490.16	SSE=146678.51 MSE=2573.30 Year=1959	74656.83
	a_1=-58.04 b_1=0.033	a_1=-61.96 b_1=0.035		a_1=-63.89 b_1=0.036	
	a_2=-19.56 b_2=0.013	a_2=-16.98 b_2=0.012		a_2= -15.67 b_2=0.011	

Sorghum-Estimation						
Model	Estimation Result	Break Year	Ljung-Box Test	Implied Growth Rate		SSE/MSE
				Beginning of the Period	End of the Period	
Simple Linear Model –No break point	a=-884.18 b=0.46	--	Reject	6.13%	1.19%	SSE=1530.81 MSE=22.51
Simple Exponential Model –No break point	a=-27.39 b=0.016	--	Reject	1.60%	1.60%	SSE=2202.44 MSE=32.39
Model 1 (Exponential + Linear-unrestricted)	a_1=-75.57 b_1=0.04	1959	Reject	4.00%	4.00%	SSE=721.02 MSE=10.92
	a_2=-450.77 b_2=0.24		Fail to Reject	1.09%	0.62%	
Model 2 (Exponential + Exponential-unrestricted)	a_1=-106.05 b_1=0.056	1964	Reject	5.6%	5.6%	SSE=694.24 MSE=10.52
	a_2=-7.90 b_2=0.006		Reject	0.6%	0.6%	
Model 3 (Linear + Exponential-unrestricted)	a_1=-803.94 b_1=0.41	1959	Reject	5.47%	2.04%	SSE=754.69 MSE=11.44
	a_2=-11.04 b_2=0.007		Fail to Reject	0.70%	0.70%	
Model 4 (Linear + Linear-unrestricted)	a_1=-803.94 b_1=0.41	1959	Reject	5.47%	2.04%	SSE=734.76 MSE=11.13
	a_2=-450.77 b_2=0.24		Fail to Reject	1.09%	0.62%	
Model 5 (Exponential + Linear-restricted)	a_1=-112.37 b_1=0.059	1966	Reject	5.90%	5.90%	SSE=694.66 MSE=10.37
	a_2=-356.76 b_2=0.20		Reject	2.67%	0.65%	
Model 6 (Exponential + Exponential-restricted)	a_1=-133.48 b_1=0.050	1966	Reject	5.00%	5.00%	SSE=699.45 MSE=10.44
	a_2=-8.13 b_2=0.005		Reject	0.50%	0.50%	
Model 7 (Linear + Exponential-restricted)	a_1=-1573.61 b_1=0.81	1972	Reject	10.8%	2.4%	SSE=838.35 MSE=12.51
	a_2=-7.04 b_2=0.005		Fail to Reject	0.50%	0.50%	
Model 8 (Linear + Linear-restricted)	a_1=-1596.32 b_1=0.83	1971	Reject	11.07%	2.78%	SSE=835.09 MSE=12.46
	a_2=-348.67 b_2=0.19		Fail to Reject	0.56%	0.49%	

Sorghum-Validation					
Model	Estimation Result-0	Estimation Result-5	Out of sample Prediction Error-5	Estimation Result-10	Out of sample Prediction Error-10
Simple Linear Model - No break point	SSE=1530.81 MSE=22.51 a=-884.18 b=0.46	SSE= 1354.87 MSE= 21.50 a=-949.44, b=0.49	219.80	SSE=883.79 MSE=15.23 a=-1085.03, b=0.56	1084.60
Model 2 (Exponential + Exponential-unrestricted)	SSE=694.24 MSE=10.52 Year=1964	SSE=644.33 MSE=10.56 Year=1964	50.01	SSE=466.23 MSE=8.32 Year=1966	425.60
	a_1=-106.05 b_1=0.056	a_1=-106.05 b_1=0.056		a_1=-113.44 b_1=0.059	
	a_2=-7.90 b_2=0.006	a_2=-8.07 b_2=0.006		a_2=-15.47 b_2=0.010	
Model 5 (Exponential + Linear-restricted)	SSE=694.66 MSE=10.37 Year=1966	SSE=644.70 MSE=10.39 Year=1966	50.02	SSE=474.81 MSE=8.33 Year=1966	392.49
	a_1=-112.37 b_1=0.059	a_1=-112.25 b_1=0.059		a_1=-107.22 b_1=0.056	
	a_2=-356.76 b_2=0.20	a_2=-360.91 b_2=0.19		a_2=-539.16 b_2=0.28	
Model 6 (Exponential + Exponential-restricted)	SSE=699.45 MSE=10.44 Year=1966	SSE=649.44 MSE=10.47 Year=1966	50.19	SSE=471.37 MSE=8.27 Year=1966	388.47
	a_1=-133.48 b_1=0.050	a_1=-113.273 b_1=0.059		a_1=-107.95 b_1=0.057	
	a_2=-8.13 b_2=0.005	a_2=-8.352 b_2=0.006		a_2=-14.25 b_2=0.009	

Oats-Estimation

Model	Estimation Result	Break Year	Ljung-Box Test	Implied Growth Rate		SSE/MSE
				Beginning of the Period	End of the Period	
Simple Linear Model –No break point	a=-924.51 b=0.49	--	Reject	1.39%	0.73%	SSE=1283.23 MSE=18.87
Simple Exponential Model –No break point	a=-15.41 b=0.010	--	Reject	1.00%	1.00%	SSE=1496.58 MSE=22.01
Model 1 (Exponential + Linear-unrestricted)	a_1=-33.25 b_1=0.019	1972	Reject	1.90%	1.90%	SSE=1015.98 MSE=15.39
	a_2=-739.38 b_2=0.40		Fail to Reject	0.84%	0.59%	
Model 2 (Exponential + Exponential-unrestricted)	a_1=-25.97 b_1=0.015	1964	Fail to Reject	1.50%	1.50%	SSE=1014.29 MSE=15.37
	a_2=-8.14 b_2=0.006		Fail to Reject	0.60%	0.60%	
Model 3 (Linear + Exponential-unrestricted)	a_1=-1201.59 b_1=0.64	1986	Fail to Reject	1.82%	1.14%	SSE=1010.37 MSE=15.31
	a_2=-15.95 b_2=0.010		Fail to Reject	1.00%	1.00%	
Model 4 (Linear + Linear-unrestricted)	a_1=-1201.59 b_1=0.64	1986	Fail to Reject	1.82%	1.14%	SSE=1005.02 MSE=15.22
	a_2=-1136.82 b_2=0.60		Fail to Reject	1.10%	0.89%	
Model 5 (Exponential + Linear-restricted)	a_1=-32.24 b_1=0.018	1968	Reject	1.80%	1.80%	SSE=1049.86 MSE=15.67
	a_2=-642.59 b_2=0.35		Fail to Reject	0.65%	0.52%	
Model 6 (Exponential + Exponential-restricted)	a_1=-31.74 b_1=0.018	1969	Fail to Reject	1.80%	1.80%	SSE=1043.15 MSE=15.57
	a_2=-8.33 b_2=0.006		Fail to Reject	0.65%	0.65%	
Model 7 (Linear + Exponential-restricted)	a_1=-1324.01 b_1=0.70	1970	Fail to Reject	1.99%	1.42%	SSE=1092.47 MSE=16.31
	a_2=-8.85 b_2=0.006		Fail to Reject	0.65%	0.65%	
Model 8 (Linear + Linear-restricted)	a_1=-1329.01 b_1=0.70	1969	Fail to Reject	1.99%	1.30%	SSE=1096.74 MSE=16.37
	a_2=-669.48 b_2=0.37		Fail to Reject	0.75%	0.55%	

Oats-Validation

Model	Estimation Result-0	Estimation Result-5	Out of sample Prediction Error-5	Estimation Result-10	Out of sample Prediction Error-10
Simple Linear Model-No break point	SSE=1283.23 MSE=18.87 a=-924.51 b=0.49	SSE=1224.99 MSE=19.44 a=-955.27, b=0.51	68.07	SSE=1171.28 MSE=20.19 a=-968.14, b=0.52	132.12
Model 2 (Exponential + Exponential-unrestricted)	SSE=1014.29 MSE=15.37 Year=1964	SSE=974.08 MSE=15.96 Year=1986	102.28	SSE=914.12 MSE=16.32 Year=1964	128.34
	a_1=-25.97 b_1=0.015	a_1=-24.36 b_1=0.014		a_1=-25.97 b_1=0.015	
	a_2=-8.14 b_2=0.006	a_2=-21.58 b_2=0.013		a_2=-6.46 b_2=0.005	
Model 4 (Linear + Linear-unrestricted)	SSE=1005.02 MSE=15.22 Year=1986	SSE=954.24 MSE=15.64 Year=1986	87.25	SSE=901.96 MSE=16.10 Year=1986	187.57
	a_1=-1201.59 b_1=0.64	a_1=-1201.59 b_1=0.63		a_1=-1201.59 b_1=0.63	
	a_2=-1136.82 b_2=0.60	a_2= -1437.57 b_2=0.75		a_2=-1582.27 b_2=0.82	
Model 6 (Exponential + Exponential-restricted)	SSE=1043.15 MSE=15.57 Year=1969	SSE=1012.48 MSE=15.57 Year=1969	30.66	SSE=944.48 MSE=16.57 Year=1969	124.14
	a_1=-31.74 b_1=0.018	a_1=-31.78 b_1=0.018		a_1=-32.58 b_1=0.019	
	a_2=-8.33 b_2=0.006	a_2=-8.30 b_2=0.006		a_2=-6.72 b_2=0.005	

Barley-Estimation

Model	Estimation Result	Break Year	Ljung-Box Test	Implied Growth Rate: Beginning of the Period	Implied Growth Rate: End of the Period	SSE/MSE
Simple Linear Model –No break point	a=-1258.70 b=0.66	--	Reject	2.87%	0.90%	SSE=909.88 MSE=13.38
Simple Exponential Model –No break point	a=-25.19 b=0.015	--	Reject	1.50%	1.50%	SSE=1214.70 MSE=17.86
Model 1 (Exponential + Linear-unrestricted)	a_1=-37.34 b_1=0.021	1984	Reject	2.10%	2.10%	SSE=767.61 MSE=11.63
	a_2=-1107.49 b_2=0.58		Fail to Reject	1.14%	0.79%	
Model 2 (Exponential + Exponential-unrestricted)	a_1=-37.96 b_1=0.021	1984	Reject	2.10%	2.10%	SSE=771.58 MSE=11.69
	a_2=-16.44 b_2=0.010		Fail to Reject	1.00%	1.00%	
Model 3 (Linear + Exponential-unrestricted)	a_1=-843.41 b_1=0.45	1963	Fail to Reject	1.96%	1.29%	SSE=776.61 MSE=11.77
	a_2=-18.21 b_2=0.011		Reject	1.10%	1.10%	
Model 4 (Linear + Linear-unrestricted)	a_1=-843.41 b_1=0.45	1963	Fail to Reject	1.96%	1.29%	SSE=772.59 MSE=11.70
	a_2=-1107.49 b_2=0.58		Reject	1.54%	0.79%	
Model 5 (Exponential + Linear-restricted)	a_1=-42.21 b_1=0.023	1969	Reject	2.30%	2.30%	SSE=831.85 MSE=12.42
	a_2=-1136.03 b_2=0.60		Reject	1.40%	0.82%	
Model 6 (Exponential + Exponential-restricted)	a_1=-36.66 b_1=0.020	1979	Reject	2.00%	2.00%	SSE=833.01 MSE=12.43
	a_2=-15.08 b_2=0.010		Reject	0.90%	0.90%	
Model 7 (Linear + Exponential-restricted)	a_1=-1357.15 b_1=0.71	1982	Reject	3.09%	1.24%	SSE=873.54 MSE=13.04
	a_2=-16.25 b_2=0.010		Fail to Reject	1.00%	1.00%	
Model 8 (Linear + Linear-restricted)	a_1=-1353.66 b_1=0.71	1981	Reject	3.09%	1.35%	SSE=884.07 MSE=13.15
	a_2=-1088.21 b_2=0.57		Reject	1.00%	0.78%	

Barley-Validation

Model	Estimation Result-0	Estimation Result-5	Out of sample Prediction Error-5	Estimation Result-10	Out of sample Prediction Error-10
Simple Linear Model-No break point	SSE=909.88 MSE=13.38 a=-1258.70 b=0.66	SSE= 821.66 MSE= 13.04 a=-1269.18, b=0.67	89.40	SSE=700.75 MSE=12.08 a=-1297.18, b=0.68	225.69
Model 1 (Exponential + Linear-unrestricted)	SSE=767.61 MSE=11.63 Year=1984	SSE=681.63 MSE=11.17 Year=1963	87.50	SSE=561.84 MSE=10.03 Year=1984	320.42
	a_1=-37.34 b_1=0.021	a_1=-28.77 b_1=0.016		a_1=-37.34 b_1=0.021	
	a_2=-1107.49 b_2=0.58	a_2=-1093.01 b_2=0.58		a_2=-1767.81 b_2=0.92	
Model 5 (Exponential + Linear-restricted)	SSE=831.85 MSE=12.42 Year=1969	SSE=745.76 MSE=12.02 Year=1969	86.26	SSE=636.82 MSE=11.17 Year=1969	198.24
	a_1=-42.21 b_1=0.023	a_1=-42.37 b_1=0.023		a_1=-41.97 b_1=0.023	
	a_2=-1136.03 b_2=0.60	a_2=-1127.02 b_2=0.59		a_2=-1165.72 b_2=0.61	
Model 6 (Exponential + Exponential-restricted)	SSE=833.01 MSE=12.43 Year=1979	SSE=746.20 MSE=12.02 Year=1979	88.97	SSE=640.08 MSE=11.23 Year=1970	227.37
	a_1=-36.66 b_1=0.020	a_1=-36.94 b_1=0.021		a_1=-42.21 b_1=0.023	
	a_2=-15.08 b_2=0.010	a_2=-14.33 b_2=0.009		a_2=-19.97 b_2=0.012	

Hay-Estimation						
Model	Estimation Result	Break Year	Ljung-Box Test	Implied Growth Rate		SSE/MSE
				Beginning of the Period	End of the Period	
Simple Linear Model –No break point	a=-38.00 b=0.02	--	Reject	1.53%	0.81%	SSE=1.62 MSE=0.023
Simple Exponential Model –No break point	a=-18.02 b=0.009	--	Reject	0.90%	0.90%	SSE=2.21 MSE=0.032
Model 1 (Exponential + Linear-unrestricted)	a_1=-31.03 b_1=0.016	1982	Reject	1.60%	1.60%	SSE=0.619 MSE=0.009
	a_2=-3.45 b_2=0.003		Fail to Reject	0.13%	0.12%	
Model 2 (Exponential + Exponential-unrestricted)	a_1=-31.03 b_1=0.016	1982	Reject	1.60%	1.60%	SSE=0.619 MSE=0.009
	a_2=-1.50 b_2=0.001		Fail to Reject	0.10%	0.10%	
Model 3 (Linear + Exponential-unrestricted)	a_1=-50.74 b_1=0.027	1977	Reject	2.06%	1.24%	SSE=0.663 MSE=0.010
	a_2=-2.12 b_2=0.002		Reject	0.20%	0.20%	
Model 4 (Linear + Linear-unrestricted)	a_1=-50.74 b_1=0.027	1977	Reject	2.06%	1.24%	SSE=0.663 MSE=0.010
	a_2=-4.94 b_2=0.004		Fail to Reject	0.17%	0.16%	
Model 5 (Exponential + Linear-restricted)	a_1=-43.25 b_1=0.022	1959	Reject	2.20%	2.20%	SSE=1.332 MSE=0.020
	a_2=-31.33 b_2=0.017		Reject	0.97%	0.69%	
Model 6 (Exponential + Exponential-restricted)	a_1=-30.52 b_1=0.016	1982	Reject	1.60%	1.60%	SSE=0.624 MSE=0.009
	a_2=-0.59 b_2=0.0007		Fail to Reject	0.07%	0.07%	
Model 7 (Linear + Exponential-restricted)	a_1=-53.17 b_1=0.028	1984	Reject	2.14%	1.14%	SSE=0.681 MSE=0.010
	a_2=-1.009 b_2=0.0009		Fail to Reject	0.09%	0.09%	
Model 8 (Linear + Linear-restricted)	a_1=-53.16 b_1=0.028	1984	Reject	2.14%	1.14%	SSE=0.681 MSE=0.010
	a_2=-1.573 b_2=0.002		Fail to Reject	0.08%	0.08%	

Hay-Validation					
Model	Estimation Result-0	Estimation Result-5	Out of sample Prediction Error-5	Estimation Result-10	Out of sample Prediction Error-10
Simple Linear Model- No break point	SSE=1.62 MSE=0.023 a=-38.00 b=0.02	SSE=1.11 MSE=0.018 a=-42.10, b=0.022	0.684	SSE=0.811 MSE=0.014 a=-45.58, b=0.024	1.417
Model 2 (Exponential + Exponential-unrestricted)	SSE=0.619 MSE=0.009 Year=1982	SSE=0.559 MSE=0.009 Year=1986	0.158	SSE=0.466 MSE= 0.008 Year=1987	1.523
	a_1=-31.03 b_1=0.016	a_1=-29.95 b_1=0.016		a_1=-29.50 b_1=0.015	
	a_2=-1.50 b_2=0.001	a_2=-8.90 b_2=0.005		a_2=-25.16 b_2=0.013	
Model 8 (Exponential + Exponential-restricted)	SSE=0.624 MSE=0.009 Year=1982	SSE=0.583 MSE=0.009 Year=1981	0.071	SSE=0.544 MSE=3.96 Year=1979	0.243
	a_1=-30.52 b_1=0.016	a_1=-30.64 b_1=0.016		a_1=-31.28 b_1=0.016	
	a_2=-0.59 b_2=0.0007	a_2=-3.48 b_2=0.002		a_2=-7.06 b_2=0.004	

APPENDIX B

Full Characterization of Solutions of the Two-Type model

Let the subscripts 1 and 2 denote the Non-additional producers and the Additional producers respectively.

1. First-best Case

$$q_1^* = \frac{\theta_2 Q_0}{\alpha_2\theta_1 + \alpha_1\theta_2} + \tilde{\zeta}$$

$$q_2^* = \frac{\theta_1 Q_0}{\alpha_2\theta_1 + \alpha_1\theta_2}$$

$$T_1^* = \frac{\theta_1\theta_2^2 Q_0^2}{\left(\alpha_2\theta_1 + \alpha_1\theta_2\right)^2}$$

$$T_2^* = \frac{\theta_2\theta_1^2 Q_0^2}{\left(\alpha_2\theta_1 + \alpha_1\theta_2\right)^2}$$

$$TC^* = \frac{\theta_1\theta_2 {Q_0}^2}{\alpha_1\theta_2 + \alpha_2\theta_1}$$

$$\frac{\partial TC^*}{\partial Q_0} = \frac{2\theta_1\theta_2 Q_0}{\alpha_1\theta_2 + \alpha_2\theta_1}$$

2. Screening contracts

1) Contract with price and quantity specifications (q_i, T_i)

When $Q_0 < \frac{\alpha_1\theta_2 + \alpha_2^2\theta_1}{\alpha_2\theta_1}\tilde{\zeta}$,

$$q_1 = \frac{\theta_2 Q_0}{\alpha_2^2\theta_1 + \alpha_1\theta_2} + \tilde{\zeta}$$

$$q_2 = \frac{\alpha_2\theta_1 Q_0}{\alpha_2^2\theta_1 + \alpha_1\theta_2}$$

$$T_1 = \frac{\theta_1\theta_2 Q_0^2(\theta_2 + \alpha_2^2\theta_1)}{\left(\alpha_2^2\theta_1 + \alpha_1\theta_2\right)^2}$$

$$T_2 = \frac{\alpha_2^2 \theta_1^2 \theta_2 Q_0^2}{\left(\alpha_2^2 \theta_1 + \alpha_1 \theta_2\right)^2}$$

$$TC = \frac{\theta_1 \theta_2 Q_0^2}{\alpha_1 \theta_2 + \alpha_2^2 \theta_1}$$

$$\frac{\partial TC}{\partial Q_0} = \frac{2\theta_1 \theta_2 Q_0}{\alpha_1 \theta_2 + \alpha_2^2 \theta_1}$$

When $Q_0 > \dfrac{\alpha_1 \theta_2 + \alpha_2^2 \theta_1}{\alpha_2 \theta_1} \tilde{\zeta}$,

$$q_1 = \frac{(\theta_2 - \alpha_1 \theta_1) Q_0}{\alpha_1 \theta_2 + \alpha_2 \theta_1 - \alpha_1 \theta_1} + \left(\frac{\alpha_1 \alpha_2 \theta_1 + \alpha_1 \theta_2 + \alpha_2 \theta_1 - \alpha_1 \theta_1}{\alpha_1 \theta_2 + \alpha_2 \theta_1 - \alpha_1 \theta_1}\right) \tilde{\zeta}$$

$$q_2 = \frac{\theta_1 (\alpha_2 Q_0 - \alpha_1^2 \tilde{\zeta})}{\alpha_1 \theta_2 + \alpha_2 \theta_1 - \alpha_1 \theta_1}$$

$$T_1 = \frac{\theta_1 \left[(\theta_2 - \alpha_1 \theta_1) Q_0 + \alpha_1 \alpha_2 \theta_1 \tilde{\zeta}\right]^2 + \theta_1 \left[\alpha_2 \theta_1 Q_0 - (\alpha_1 \theta_2 + \alpha_2 \theta_1) \tilde{\zeta}\right]^2 + \theta_2 \theta_1 (\alpha_2 Q_0 - \alpha_1 \tilde{\zeta})}{(\alpha_1 \theta_2 + \alpha_2 \theta_1 - \alpha_1 \theta_1)^2}$$

$$T_2 = \frac{\theta_2 \theta_1^2 (\alpha_2 Q_0 - \alpha_1^2 \tilde{\zeta})}{(\alpha_1 \theta_2 + \alpha_2 \theta_1 - \alpha_1 \theta_1)^2}$$

$$TC = \frac{\alpha_1 \theta_1 \{\left[(\theta_2 - \alpha_1 \theta_1) Q_0 + \alpha_1 \alpha_2 \theta_1 \tilde{\zeta}\right]^2 + \left[\alpha_2 \theta_1 Q_0 - \left(\alpha_1 \theta_2 + \alpha_2^2 \theta_1\right) \tilde{\zeta}\right]^2\} + \alpha_2 \theta_2 \theta_1^2 (\alpha_2 Q_0 - \alpha_1^2 \tilde{\zeta})}{(\alpha_1 \theta_2 + \alpha_2 \theta_1 - \alpha_1 \theta_1)^2}$$

$$\frac{\partial TC}{\partial Q_0} = \frac{2\theta_1 (\theta_2 - \alpha_1 \theta_1) Q_0}{\alpha_1 \theta_2 + \alpha_2 \theta_1 - \alpha_1 \theta_1} + \frac{2\alpha_1 \alpha_2 \theta_1^2 \tilde{\zeta}}{\alpha_1 \theta_2 + \alpha_2 \theta_1 - \alpha_1 \theta_1}$$

2) Contract with price specification only (t_i, S_i)

When $Q_0 < \dfrac{\alpha_1^2 \theta_2}{\alpha_2 \theta_1} \tilde{\zeta}$,

$$q_1 = \frac{Q_0}{\alpha_1} + \tilde{\zeta}$$

$$q_2 = 0$$

$$t_1 = \frac{2\theta_1 Q_0}{\alpha_1}$$

$$t_2 = 0$$

$$S_1 = \frac{\theta_1 (Q_0^2 + 2\alpha_1 Q_0 \tilde{\zeta})}{\alpha_1^2}$$

$$S_2 = 0$$

$$TC = \frac{\theta_1 Q_0^2}{\alpha_1}$$

$$\frac{\partial TC}{\partial Q_0} = \frac{2\theta_1 Q_0}{\alpha_1}$$

When $Q_0 \geq \frac{\alpha_1^2\theta_2}{\alpha_2\theta_1}\tilde{\zeta}$,

$$q_1 = \frac{\theta_2\left[\theta_1\left(\alpha_2 - \alpha_1\right) + \alpha_1\theta_2\right]Q_0 + [\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(2\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2]\tilde{\zeta}}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2}$$

$$q_2 = \frac{\theta_1\left[\alpha_2\theta_1 Q_0 - \alpha_1^2\theta_2\tilde{\zeta}\right]}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2}$$

$$t_1 = 2\theta_1\left(q_1 - \tilde{\zeta}\right) \text{[illegible]} \frac{\theta_2\left[\theta_1\left(\alpha_2 - \alpha_1\right) + \alpha_1\theta_2\right]Q_0 + \theta_1\theta_2\alpha_1\alpha_2\tilde{\zeta})}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2}$$

$$t_2 = 2\theta_2 q_2 = \frac{2\theta_1\theta_2\left[\alpha_2\theta_1 Q_0 - \alpha_1^2\theta_2\tilde{\zeta}\right]}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2}$$

$$S_1 = 2\theta_1\left(q_1 - \tilde{\zeta}\right) \text{[illegible]}$$

$$S_2 = \theta_2 q_2^2$$

$$TC = \frac{\theta_1\theta_2\left(\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1\right)Q_0^2 + 2\theta_1^2\theta_2\alpha_1\alpha_2 Q_0\tilde{\zeta} \text{[illegible]}}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2}$$

$$\frac{\partial TC}{\partial Q_0} = \frac{2\theta_1\theta_2\left(\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1\right)Q_0 + 2\theta_1^2\theta_2\alpha_1\alpha_2\tilde{\zeta}}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2}$$

3. Non-screening Contracts

1) Uniform price method

$$q_1 = \frac{\theta_2 Q_0}{\alpha_2\theta_1 + \alpha_1\theta_2} + \tilde{\zeta}$$

$$q_2 = \frac{\theta_1 Q_0}{\alpha_2\theta_1 + \alpha_1\theta_2}$$

$$t = \frac{2\theta_1\theta_2 Q_0}{\alpha_1\theta_2 + \alpha_2\theta_1}$$

$$TC = \frac{2\theta_1\theta_2}{\alpha_1\theta_2 + \alpha_2\theta_1} Q_0^2 + \frac{2\alpha_1\theta_1\theta_2}{\alpha_1\theta_2 + \alpha_2\theta_1} Q_0\tilde{\zeta}$$

$$\frac{\partial TC}{\partial Q_0} = \frac{4\theta_1\theta_2}{\alpha_1\theta_2 + \alpha_2\theta_1} Q_0 + \frac{2\alpha_1\theta_1\theta_2}{\alpha_1\theta_2 + \alpha_2\theta_1} \tilde{\zeta}$$

2) Baseline method

a) Baseline-the Business as Usual Case

When $Q_0 < \frac{2\alpha_1\theta_2}{\theta_1}\tilde{\zeta}$,

$$q_1 = \frac{Q_0}{\alpha_1} + \tilde{\zeta}$$

$$q_2 = 0$$

$$t = \frac{2\theta_1 Q_0}{\alpha_1}$$

$$TC = \frac{2\theta_1 Q_0^2}{\alpha_1}$$

When $\frac{2\alpha_1\theta_2\tilde{\zeta}}{\theta_1} \leq Q_0 < \frac{2(\alpha_1\theta_2 + \alpha_2\theta_1)\tilde{\zeta}}{\theta_1}$,

$$q_1 = \frac{Q_0}{\alpha_1} + \tilde{\zeta}$$

$$q_2 = 2\tilde{\zeta}$$

$$t = 4\theta_2\tilde{\zeta}$$

The target constraint will not be binding, i.e. $\alpha_1\left(q_1 - \tilde{\zeta}\right) + \alpha_2 q_2 = Q_0\left(1 + \frac{\alpha_2\theta_1}{\alpha_1\theta_2}\right) > Q_0$.

It is not clear what the production allocation would be and there may not be equilibrium.

But with ancillary constraints, the supply function can be smoothed.

When $Q_0 \geq \frac{2(\alpha_1\theta_2 + \alpha_2\theta_1)}{\theta_1}\tilde{\zeta}$,

$$q_1 = \frac{\theta_2 Q_0}{\alpha_2\theta_1 + \alpha_1\theta_2} + \tilde{\zeta}$$

$$q_2 = \frac{\theta_1 Q_0}{\alpha_2\theta_1 + \alpha_1\theta_2}$$

$$t = \frac{2\theta_1\theta_2 Q_0}{\alpha_1\theta_2 + \alpha_2\theta_1}$$

$$TC = \frac{2\theta_1\theta_2}{\alpha_1\theta_2 + \alpha_2\theta_1} Q_0^2 - \frac{2\alpha_2\theta_1\theta_2}{\alpha_1\theta_2 + \alpha_2\theta_1} Q_0 \tilde{\zeta}$$

APPENDIX C

Analytical Derivation of Numerical Results

C.1 Comparison between the total cost of Baseline_low and Baseline_both

If $\frac{\theta_2}{\theta_1} \geq \frac{\sqrt{\alpha_2^2 + \frac{1}{4}} + \frac{1}{2}}{\alpha_1}$, $TC^{Baseline\_both} \geq TC^{Baseline\_low} \forall Q_0$.

If $\frac{\theta_2}{\theta_1} < \frac{\sqrt{\alpha_2^2 + \frac{1}{4}} + \frac{1}{2}}{\alpha_1}$,

$\exists Q_0^*, TC^{Baseline\_both} \geq TC^{Baseline\_low} \forall Q_0 \leq Q_0^*, TC^{Baseline\_both} < TC^{Baseline\_low}, otherwise$.

[Proof]

$$TC^{Baseline_{low}} = \frac{\theta_1}{\alpha_1} Q_0^2$$
$$\frac{\partial TC^{Baseline_{low}}}{\partial Q_0} = \frac{2\theta_1}{\alpha_1} Q_0$$
$$\frac{\partial^2 TC^{Baseline\_low}}{\partial {Q_0}^2} = \frac{2\theta_1}{\alpha_1}$$
$$TC^{Baseline_{both}} = \frac{\theta_1\theta_2\left[\left(2\theta_2 - \theta_1\right)\alpha_1 + \theta_1\alpha_2\right]Q_0^2}{\left(\theta_2\alpha_1 + \theta_1\alpha_2\right)^2} + \frac{2\alpha_1\theta_1\theta_2 Q_0 \tilde{\zeta}}{\theta_2\alpha_1 + \theta_1\alpha_2}$$
$$\frac{\partial TC^{Baseline\_both}}{\partial Q_0} = \frac{2\theta_1\theta_2[\left(2\theta_2 - \theta_1\right)\alpha_1 + \theta_1\alpha_2]}{(\theta_2\alpha_1 + \theta_1\alpha_2)^2} Q_0 + \frac{2\alpha_1\theta_1\theta_2\tilde{\zeta}}{\theta_2\alpha_1 + \theta_1\alpha_2}$$
$$\frac{\partial^2 TC^{Baseline\_both}}{\partial {Q_0}^2} = \frac{2\theta_1\theta_2[\left(2\theta_2 - \theta_1\right)\alpha_1 + \theta_1\alpha_2]}{(\theta_2\alpha_1 + \theta_1\alpha_2)^2}$$

If $\frac{2\theta_1\theta_2[\left(2\theta_2 - \theta_1\right)\alpha_1 + \theta_1\alpha_2]}{(\theta_2\alpha_1 + \theta_1\alpha_2)^2} \geq \frac{2\theta_1}{\alpha_1}$, Then,

$$\frac{\partial TC^{Baseline\_both}}{\partial Q_0} = \frac{2\theta_1\theta_2[(2\theta_2-\theta_1)\alpha_1+\theta_1\alpha_2]}{(\theta_2\alpha_1+\theta_1\alpha_2)^2}Q_0 + \frac{2\alpha_1\theta_1\theta_2\tilde{\zeta}}{\theta_2\alpha_1+\theta_1\alpha_2} \geq \frac{2\theta_1}{\alpha_1}Q_0 = \frac{\partial TC^{Baseline\_low}}{\partial Q_0}, \forall Q_0$$

$$\Rightarrow \int_0^{Q_0} \frac{2\theta_1\theta_2[(2\theta_2-\theta_1)\alpha_1+\theta_1\alpha_2]}{(\theta_2\alpha_1+\theta_1\alpha_2)^2}q + \frac{2\alpha_1\theta_1\theta_2\tilde{\zeta}}{\theta_2\alpha_1+\theta_1\alpha_2}dq \geq \int_0 \frac{2\theta_1}{\alpha_1}qdq, \forall Q_0$$

$$\Rightarrow TC^{Baseline\_both} \geq TC^{Baseline\_low}, \forall Q_0$$

$\frac{2\theta_1\theta_2[(2\theta_2-\theta_1)\alpha_1+\theta_1\alpha_2]}{(\theta_2\alpha_1+\theta_1\alpha_2)^2} \geq \frac{2\theta_1}{\alpha_1}$ needs

$$\frac{2\theta_1\theta_2\left[(2\theta_2-\theta_1)\alpha_1+\theta_1\alpha_2\right]}{(\theta_2\alpha_1+\theta_1\alpha_2)^2} \geq \frac{2\theta_1}{\alpha_1} \quad \frac{\theta_2\left[(2\theta_2-\theta_1)\alpha_1+\theta_1\alpha_2\right]}{(\theta_2\alpha_1+\theta_1\alpha_2)^2} \geq \frac{1}{\alpha_1}$$

$$\Leftrightarrow \alpha_1\theta_2\left[(2\theta_2-\theta_1)\alpha_1+\theta_1\alpha_2\right] \geq (\theta_2\alpha_1+\theta_1\alpha_2)^2$$

$$\Leftrightarrow \alpha_1 a\left[(2a-1)\alpha_1+\alpha_2\right] \geq (a\alpha_1+\alpha_2)^2 \qquad (\theta_2 = a\theta_1)$$

$$\Leftrightarrow 2a^2\alpha_1^2 - a\alpha_1^2 + a\alpha_1\alpha_2 \geq a^2\alpha_1^2 + 2a\alpha_1\alpha_2 + \alpha_2^2$$

$$\Leftrightarrow a^2\alpha_1^2 - a\alpha_1^2 \geq a\alpha_1\alpha_2 + \alpha_2^2$$

$$\Leftrightarrow a^2\alpha_1^2 - a\alpha_1 \geq \alpha_2^2 \qquad (\alpha_1+\alpha_2=1)$$

$$\Leftrightarrow a^2\alpha_1^2 - a\alpha_1 + \frac{1}{4} \geq \alpha_2^2 + \frac{1}{4}$$

$$\Leftrightarrow \left(a\alpha_1 - \frac{1}{2}\right)^2 \geq \alpha_2^2 + \frac{1}{4}$$

$$\Leftrightarrow a \geq \frac{\sqrt{\alpha_2^2+\frac{1}{4}}+\frac{1}{2}}{\alpha_1}.$$

As figure C.1 shows, the first derivative of $TC^{Baseline\_both}$ represented by the line DC is greater than that of $TC^{Baseline\_low}$ represented by the line OB everywhere. For a given target Q_0 (OA), $TC^{Baseline\_both}$ equals the area of OACD and $TC^{Baseline\_low}$ equals the area of OAB. $TC^{Baseline\_both}$ is greater than $TC^{Baseline\_low}$ everywhere and it is always optimal to leave the additional type out of the program.

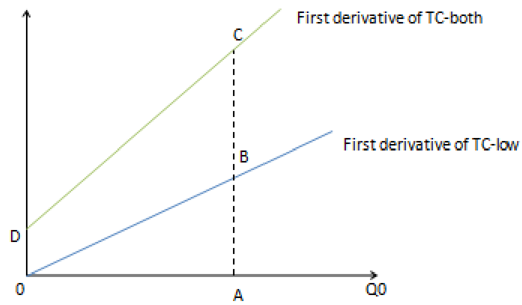

Figure C.1: Derivatives of $TC^{Baseline\_both}$ and $TC^{Baseline\_low}$ without Interception.
$\left(\frac{\theta_2}{\theta_1} \geq \frac{\sqrt{\alpha_2^2 + \frac{1}{4}} + \frac{1}{2}}{\alpha_1}\right)$

Otherwise,

$\frac{2\theta_1\theta_2[(2\theta_2-\theta_1)\alpha_1+\theta_1\alpha_2]}{(\theta_2\alpha_1+\theta_1\alpha_2)^2} < \frac{2\theta_1}{\alpha_1}$, the second derivative of $TC^{Baseline\_both}$ is less than that of $TC^{Baseline\_low}$.

$$\exists Q_0^* = \frac{\alpha_1^2\theta_2(\alpha_1\theta_2+\alpha_2\theta_1)}{\alpha_2^2\theta_1^2-\alpha_1^2\theta_2^2+\alpha_1\theta_1\theta_2}\tilde{\zeta},$$

$$\frac{\partial TC^{Baseline\_both}}{\partial Q_0} = \frac{2\theta_1\theta_2\left[\left(2\theta_2-\theta_1\right)\alpha_1+\theta_1\alpha_2\right]}{\left(\theta_2\alpha_1+\theta_1\alpha_2\right)^2}Q_0 + \frac{2\alpha_1\theta_1\theta_2\tilde{\zeta}}{\theta_2\alpha_1+\theta_1\alpha_2} \geq \frac{2\theta_1}{\alpha_1}Q_0 = \frac{\partial TC^{Baseline\_low}}{\partial Q_0}\forall Q_0 \leq Q_0^*$$

$$\frac{\partial TC^{Baseline\_both}}{\partial Q_0} < \frac{\partial TC^{Baseline\_low}}{\partial Q_0}\forall Q_0 > Q_0^*$$

$$\exists Q_0^{**} = \frac{2\alpha_1^2\theta_2(\alpha_1\theta_2+\alpha_2\theta_1)}{\alpha_2^2\theta_1^2-\alpha_1^2\theta_2^2+\alpha_1\theta_1\theta_2}\tilde{\zeta},$$

$$TC^{Baseline\_both} = \int_0^{Q_0} \frac{2\theta_1\theta_2\left[\left(2\theta_2-\theta_1\right)\alpha_1+\theta_1\alpha_2\right]}{\left(\theta_2\alpha_1+\theta_1\alpha_2\right)^2}q + \frac{2\alpha_1\theta_1\theta_2\tilde{\zeta}}{\theta_2\alpha_1+\theta_1\alpha_2}dq \geq \int_0 \frac{2\theta_1}{\alpha_1}qdq = TC^{Baseline\_low}\forall Q_0 \leq Q_0^{**}$$

$TC^{Baseline\_both} < TC^{Baseline\_low} \forall Q_0 > Q_0^{**}$

The first derivative of $TC^{Baseline\_both}$ is greater than that of $TC^{Baseline\_low}$ when Q_0 is small but increases slower as Q_0 keeps increasing. When Q_0 is larger than Q_0^*, it will less than that of $TC^{Baseline\_low}$. And as Q_0 keeps increasing, the cost minimization solution will switch from leaving the additional type out of the program to being open to both types at $Q_0 = Q_0^{**}$ (figure C.2).

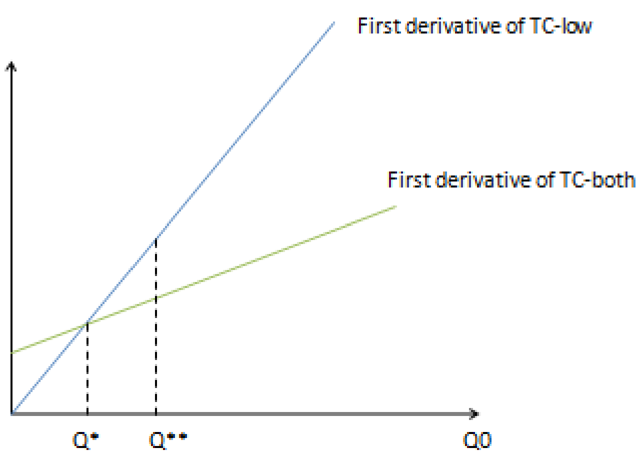

Figure C.2: Derivatives of $TC^{Baseline\_both}$ and $TC^{Baseline\_low}$ with Interception·
$(\frac{\theta_2}{\theta_1} < \frac{\sqrt{\alpha_2^2 + \frac{1}{4}} + \frac{1}{2}}{\alpha_1})$

C.2 Cost effectiveness comparisons

1) Screening contract with price and quantity specifications (a) versus screening contract with price specifications only (b): $TC_a \leq TC_b$

[Proof]

$$TC_a = \begin{cases} \dfrac{\theta_1\theta_2 Q_0^2}{\alpha_1\theta_2+\alpha_2^2\theta_1}, Q_0 < \dfrac{\alpha_1\theta_2+\alpha_2^2\theta_1}{\alpha_2\theta_1}\tilde{\zeta} \\ \dfrac{\alpha_1\theta_1\{\left[(\theta_2-\alpha_1\theta_1)Q_0+\alpha_1\alpha_2\theta_1\tilde{\zeta}\right]^2 \cdots \theta_1 Q_0-\left(\alpha_1\theta_2+\alpha_2^2\theta_1\right)\tilde{\zeta}\right]^2, \cdots \theta_1^2(\alpha_2 Q_0-\alpha_1^2\tilde{\zeta} \cdots}{(\alpha_1\theta_2+\alpha_2\theta_1-\alpha_1\theta_1)^2}, otherwise \end{cases}$$

$$TC_b = \begin{cases} \dfrac{\theta_1 Q_0^2}{\alpha_1}, Q_0 < \dfrac{\alpha_1^2\theta_2}{\alpha_2\theta_1}\tilde{\zeta} \\ \dfrac{\theta_1\theta_2\left(\alpha_1\theta_2-\alpha_1\theta_1+\alpha_2\theta_1\right)Q_0^2+2\theta_1^2\theta_2\alpha_1\alpha_2 Q_0\tilde{\zeta} \cdots \tilde{\zeta}}{\theta_1^2\alpha_2^2+\theta_1\theta_2\alpha_1\left(\alpha_2-\alpha_1\right)+\alpha_1^2\theta_2^2}, otherwise \end{cases}$$

If $Q_0 < \dfrac{\alpha_1^2\theta_2}{\alpha_2\theta_1}\tilde{\zeta}$,

$$TC_{\mathrm{b}} = \frac{\theta_1 Q_0^2}{\alpha_1} \geq \frac{\theta_1\theta_2 Q_0^2}{\alpha_1\theta_2+\alpha_2^2\theta_1} = TC_{\mathrm{a}} \Leftrightarrow \frac{1}{\alpha_1} \geq \frac{\theta_2}{\alpha_1\theta_2+\alpha_2^2\theta_1} \Leftrightarrow 1 \geq \frac{\alpha_1\theta_2}{\alpha_1\theta_2+\alpha_2^2\theta_1}.$$

If $Q_0 \geq \dfrac{\alpha_1^2\theta_2}{\alpha_2\theta_1}\tilde{\zeta}$,

$$TC_{a(q_1^a,q_2^a)} \leq TC'_{a(q_1^b,q_2^b)} < TC_{b(q_1^b,q_2^b)},$$

where $TC_{a(q_1^a,q_2^a)}$ is the total cost of the screening contract scheme with price and quantity specifications at the allocation where the total cost is minimized. $TC'_{a(q_1^b,q_2^b)}$ is the total cost of the screening contract scheme with price and quantity specifications at the allocation where the total cost of the screening contract scheme with price specifications only is minimized. $TC_{b(q_1^b,q_2^b)}$ is the total cost of the screening contract scheme with price specifications only at the allocation where the total cost of the screening contract scheme with price specifications only is minimized.

The first inequality is established by the nature of the minimization problem.

The second inequality is established as follows:

Given the target Q_0 with α_1 and α_2, for any allocation (q_1, q_2) that satisfies

$\alpha_1(q_1 - \tilde{\zeta}$ [illegible] $= Q_0$,

$TC = \alpha_1$*(Production cost of producing q_1 + Information Rent)+ α_2*Production cost of producing q_2, where information rent is no less than the profit of mimicking the additional producers which is always greater under the screening contract with price specification only. In figure C.3, suppose the optimal production quantity for the Additional type is q_2, under the screening contract scheme with price and quantity specifications, information rent paid to the Non-additional producers equals the production cost difference between the two types (i.e. the area of O$\tilde{\zeta}$ [illegible]). Under the screening contract scheme with price specifications only, to induce the Additional producers to produce q_2 the unit payment needs to be set at t_2=OE and the lump-sum that the producers need to pay back equals to the area of OED. If the Non-additional producers choose to mimic the Additional producers, he would produce q_1' instead of q_2 and receive information rent equals the area of O$\tilde{\zeta}$ [illegible] . And it is clear that the area of O$\tilde{\zeta}$ [illegible] is less than the area of O$\tilde{\zeta}$ [illegible] .

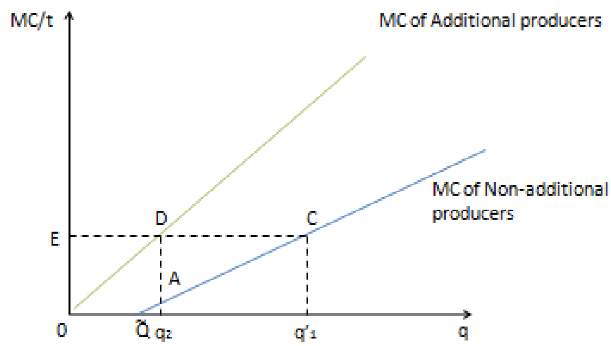

Figure C.3: Information Rent under Different Variants of Screening Contract Schemes

2) Screening contract with price specifications (a) versus optimal baseline (b):

$TC_a \leq TC_b$

[Proof]

$$TC_a = \begin{cases} \dfrac{\theta_1 Q_0^2}{\alpha_1}, Q_0 < \dfrac{\alpha_1^2\theta_2}{\alpha_2\theta_1}\tilde{\zeta} \\ \dfrac{\theta_1\theta_2\left(\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1\right)Q_0^2 + 2\theta_1^2\theta_2\alpha_1\alpha_2 Q_0\tilde{\zeta}}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2}, otherwise \end{cases}$$

$$TC_b = min\left(TC^{Baseline\_low}, TC^{Baseline\_both}\right)$$

$$TC^{Baseline\_low} = \frac{\theta_1}{\alpha_1}Q_0^2 = \int_0^{Q_0}\frac{2\theta_1}{\alpha_1}qdq$$

$$TC^{Baseline\_both} = \frac{\theta_1\theta_2[(2\theta_2 - \theta_1)\alpha_1 + \theta_1\alpha_2]Q_0^2}{(\theta_2\alpha_1 + \theta_1\alpha_2)^2} + \frac{2\alpha_1\theta_1\theta_2 Q_0\tilde{\zeta}}{\theta_2\alpha_1 + \theta_1\alpha_2} = \int_0 \frac{\theta_2[(2\theta_2 - \theta_1)\alpha_1 + \theta_1\alpha_2]}{(\theta_2\alpha_1 + \theta_1\alpha_2)^2}q + \frac{2\alpha_1\theta_1\theta_2\tilde{\zeta}}{\theta_2\alpha_1 + \theta_1\alpha_2}dq$$

In figure C.4, the segmented line OAB is the first derivative of the TC_a and therefore for given target Q_0, TC_a equals the area underneath the line. The lines OAE and CD are the first derivatives of $TC^{Baseline\_low}$ and $TC^{Baseline\_both}$ respectively and accordingly the areas underneath these two lines represent $TC^{Baseline\_low}$ and

$TC^{Baseline\_both}$. As OAB is the lowest line among the three (See Detail 1 and 2 below), it follows that:

$$TC_a \le TC^{Baseline\_low},\ and\ TC_a \le TC^{Baseline\_low} \Rightarrow TC_a \le TC_b = min\left(TC^{Baseline\_low}, TC^{Baseline\_both}\right).$$

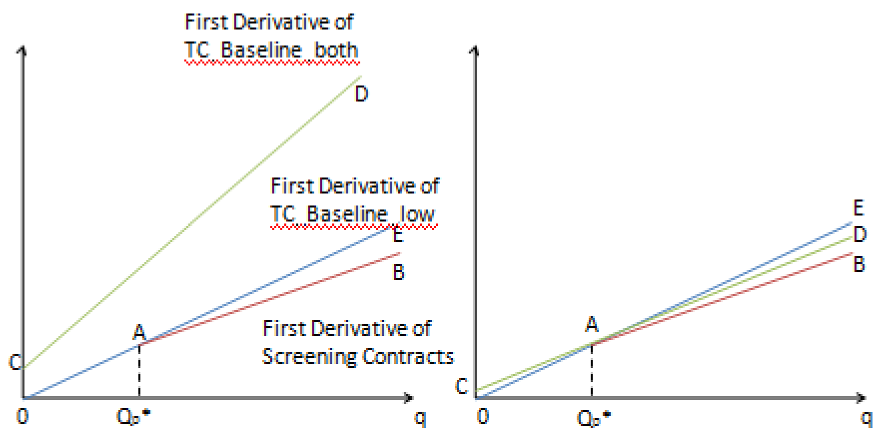

Figure C.4: Total Costs of Screening Contract with Price Specifications versus Optimal Baseline

Detail 1: $y_{OAE} \ge y_{OAB} \forall q$

OAE: $y = \dfrac{2\theta_1}{\alpha_1} q$

OAB: $$y = \begin{cases} \dfrac{2\theta_1}{\alpha_1} q \forall q \le \dfrac{\alpha_1^2\theta_2}{\alpha_2\theta_1}\tilde{\zeta} \\ \dfrac{2\theta_1\theta_2\left(\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1\right)q + 2\theta_1^2\theta_2\alpha_1\alpha_2\tilde{\zeta}}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2} \forall q > \dfrac{\alpha_1\theta_2}{\alpha_2\theta_1}\tilde{\zeta} \end{cases}$$

When $q \le \dfrac{\alpha_1^2\theta_2}{\alpha_2\theta_1}\tilde{\zeta}$, $y_{OAE} = y_{OAB}$

When $q > \frac{\alpha_1^2\theta_2}{\alpha_2\theta_1}\tilde{\zeta}$,

$$y_{OAE} - y_{OAB} = \frac{2\theta_1}{\alpha_1}q - \frac{2\theta_1\theta_2\left(\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1\right)q + 2\theta_1^2\theta_2\alpha_1\alpha_2\tilde{\zeta}}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2}$$

$$= \frac{\{2\theta_1\left(\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2\right) - 2\alpha_1\theta_1\theta_2\left(\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1\right)\}q - 2\theta_1^2\theta_2\alpha_1^2\alpha_2\tilde{\zeta}}{\alpha_1(\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2)}$$

$$= \frac{2\theta_1\{\left(\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2\right) - \left(\alpha_1^2\theta_2^2 - \alpha_1^2\theta_1\theta_2 + \alpha_1\alpha_2\theta_1\theta_2\right)\}q - 2\theta_1^2\theta_2\alpha_1^2\alpha_2\tilde{\zeta}}{\alpha_1(\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2)}$$

$$= \frac{2\theta_1^2\alpha_2(\theta_1\alpha_2 q - \theta_2\alpha_1^2\tilde{\zeta})}{\alpha_1(\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2)} > 0$$

Detail 2: $y_{CD} \ge y_{OAB} \forall q$

CD: $y = \frac{2\theta_1\theta_2[\left(2\theta_2 - \theta_1\right)\alpha_1 + \theta_1\alpha_2]}{(\theta_2\alpha_1 + \theta_1\alpha_2)^2}q + \frac{2\alpha_1\theta_1\theta_2\tilde{\zeta}}{\theta_2\alpha_1 + \theta_1\alpha_2}$

OAB: $y = \begin{cases} \frac{2\theta_1}{\alpha_1}q \forall q \le \frac{\alpha_1^2\theta_2}{\alpha_2\theta_1}\tilde{\zeta} \\ \frac{2\theta_1\theta_2\left(\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1\right)q + 2\theta_1^2\theta_2\alpha_1\alpha_2\tilde{\zeta}}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2} \forall q > \frac{\alpha_1^2\theta_2}{\alpha_2\theta_1}\tilde{\zeta} \end{cases}$

When $q \le \frac{\alpha_1^2\theta_2}{\alpha_2\theta_1}\tilde{\zeta}$, $y_{CD} \ge y_{OAB}$ (See C.1 in Appendix C)

When $q > \frac{\alpha_1^2\theta_2}{\alpha_2\theta_1}\tilde{\zeta}$,

$$\frac{2\theta_1\theta_2\left[\left(2\theta_2 - \theta_1\right)\alpha_1 + \theta_1\alpha_2\right]}{\left(\theta_2\alpha_1 + \theta_1\alpha_2\right)^2} \ge \frac{2\theta_1\theta_2\left(\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1\right)}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2}$$

$$\Leftrightarrow \frac{2\theta_2\alpha_1 - \theta_1\alpha_1 + \theta_1\alpha_2}{\left(\theta_2\alpha_1 + \theta_1\alpha_2\right)^2} \ge \frac{\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2}$$

$$\Leftrightarrow (\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1)\left(\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2\right) + \alpha_1\theta_2\left(\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2\right)$$

$$\ge (\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1)\left(\theta_2\alpha_1 + \theta_1\alpha_2\right)^2$$

$$\Leftrightarrow (\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1)\left(\theta_1\theta_2\alpha_1\left(-\alpha_2 - \alpha_1\right)\right) + \alpha_1\theta_2\left(\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2\right) \ge 0$$

$$\Leftrightarrow (\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1)\left(-\theta_1\right) + \left(\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2\right) \ge 0$$

$$\Leftrightarrow (\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1)\left(-\theta_1\right) + \left(\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2\right) \ge 0$$

$$\Leftrightarrow \theta_1^2\left(\alpha_1 - \alpha_2 + \alpha_2^2\right) + \theta_1\theta_2\alpha_1\left(-1 + \alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2 \geq 0$$

$$\Leftrightarrow \alpha_1^2\left(\theta_1^2 - 2\theta_1\theta_2 + \theta_2^2\right) \geq 0$$

$$\Leftrightarrow \alpha_1^2\left(\theta_1 - \theta_2\right)^2 \geq 0$$

$$\frac{2\alpha_1\theta_1\theta_2\tilde{\zeta}}{\theta_2\alpha_1 + \theta_1\alpha_2} \geq \frac{2\theta_1^2\theta_2\alpha_1\alpha_2\tilde{\zeta}}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2}$$

$$\Leftrightarrow \frac{1}{\theta_2\alpha_1 + \theta_1\alpha_2} \geq \frac{\theta_1\alpha_2}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2}$$

$$\Leftrightarrow \theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2 \geq \theta_1\alpha_2\left(\theta_2\alpha_1 + \theta_1\alpha_2\right)$$

$$\Leftrightarrow \theta_1\theta_2\alpha_1\left(-\alpha_1\right) + \alpha_1^2\theta_2^2 \geq 0$$

$$\Leftrightarrow \alpha_1^2\theta_2(\theta_2 - \theta_1) \geq 0$$

$$\left.\begin{array}{l} \dfrac{2\theta_1\theta_2\left[\left(2\theta_2 - \theta_1\right)\alpha_1 + \theta_1\alpha_2\right]}{\left(\theta_2\alpha_1 + \theta_1\alpha_2\right)^2} \geq \dfrac{2\theta_1\theta_2\left(\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1\right)}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2} \\ \dfrac{2\alpha_1\theta_1\theta_2\tilde{\zeta}}{\theta_2\alpha_1 + \theta_1\alpha_2} \geq \dfrac{2\theta_1^2\theta_2\alpha_1\alpha_2\tilde{\zeta}}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2} \end{array}\right\} \Rightarrow y_{CD} > y_{OAB}$$

3) Optimal baseline (a) versus baseline_business as usual (b): $TC_a \leq TC_b$.

[Proof]: by the nature of the minimization problem.

4) Baseline_business as usual (a) versus uniform price (b):

When $Q_0 < \frac{2(\alpha_1\theta_2 + \alpha_2\theta_1)}{\theta_1}\tilde{\zeta}$, the relationship between TC_a and TC_b is unclear, see numerical simulation example in Section 3.

When $Q_0 \geq \frac{2(\alpha_1\theta_2 + \alpha_2\theta_1)}{\theta_1}\tilde{\zeta}$, $TC_a < TC_b$ as:

$$TC_a - TC_b = \frac{2\theta_1\theta_2}{\alpha_1\theta_2 + \alpha_2\theta_1}Q_0^2 - \frac{2\alpha_2\theta_1\theta_2}{\alpha_1\theta_2 + \alpha_2\theta_1}Q_0\tilde{\zeta} \quad \frac{\theta_2}{\alpha_1\theta_2 + \alpha_2\theta_1}Q_0^2 - \frac{2\alpha_1\theta_1\theta_2}{\alpha_1\theta_2 + \alpha_2\theta_1}Q_0\tilde{\zeta} \quad \frac{}{\alpha_1\theta_2 + \alpha_2\theta_1}$$

C.3 Convergence of ratio of total costs of different methods relative to that of the first best case as Q_0 goes to infinity

1) $TC^{ScreeningContractwithPriceandQuantity} \Big/ TC^{Firstbest}$

$$\lim_{Q_0 \to \infty} \frac{TC^{ScreeningContractwithPriceandQuantity}}{TC^{FirstBest}}$$

$$= \lim_{Q_0 \to \infty} \frac{\dfrac{\alpha_1 \theta_1 \left\{ \left[(\theta_2 - \alpha_1 \theta_1) Q_0 + \alpha_1 \alpha_2 \theta_1 \tilde{Q} \right. \text{[illegible]} \right.}{\left(\alpha_1 \theta_2 + \alpha_2 \theta_1 - \alpha_1 \theta_1 \right)^2}}{\dfrac{\theta_1 \theta_2 Q_0^{\,2}}{\alpha_1 \theta_2 + \alpha_2 \theta_1}}$$

$$= \frac{\dfrac{\alpha_1 \theta_1 \left(\theta_2 - \alpha_1 \theta_1 \right)^2 - \alpha_1 \theta_1^3 \alpha_2^2 + \alpha_2^2 \theta_2 \theta_1^2}{\left(\alpha_1 \theta_2 + \alpha_2 \theta_1 - \alpha_1 \theta_1 \right)^2}}{\dfrac{\theta_1 \theta_2}{\alpha_1 \theta_2 + \alpha_2 \theta_1}}$$

$$= \frac{\left(\alpha_1 \theta_2 + \alpha_2 \theta_1 \right) \left(\alpha_1 \left(\theta_2 - \alpha_1 \theta_1 \right)^2 - \alpha_1 \theta_1^2 \alpha_2^2 + \alpha_2^2 \theta_2 \theta_1 \right)}{\theta_2 \left(\alpha_1 \theta_2 + \alpha_2 \theta_1 - \alpha_1 \theta_1 \right)^2}$$

$$= \frac{\left(\alpha_1 \theta_2 + \alpha_2 \theta_1 \right) \left(\alpha_1 \theta_2^2 + \theta_1 \theta_2 \left(\alpha_2 - \alpha_1 - \alpha_1^2 \right) + \alpha_1 \theta_1^2 \left(\alpha_1 - \alpha_2 \right) \right)}{\theta_2 \left(\alpha_1 \theta_2 + \alpha_2 \theta_1 - \alpha_1 \theta_1 \right)^2}$$

$$= \frac{\left(\alpha_1 a + \alpha_2 \right) \left(\alpha_1 a^2 + a \left(\alpha_2 - \alpha_1 - \alpha_1^2 \right) + \alpha_1 \left(\alpha_1 - \alpha_2 \right) \right)}{a \left(\alpha_1 a + \alpha_2 - \alpha_1 \right)^2} \quad \left(a = \frac{\theta_2}{\theta_1} \right)$$

For

$$a = 1, \lim_{Q_0 \to \infty} \frac{TC^{ScreeningContractwithPriceandQuantity}}{TC^{FirstBest}} = \frac{\left(\alpha_1 + \alpha_2 \right) \left(\alpha_1 + \alpha_2 - \alpha_1 - \alpha_1^2 + \alpha_1^2 - \alpha_1 \alpha_2 \right)}{\left(\alpha_1 + \alpha_2 - \alpha_1 \right)^2} = 1$$

2) $TC^{ScreeningContractwithPrice} \Big/ TC^{FirstBest}$

$$\lim_{Q_0 \to \infty} \frac{TC^{ScreeningContractwithPrice}}{TC^{FirstBest}}$$

$$= \lim_{Q_0 \to \infty} \frac{\dfrac{\theta_1\theta_2\left(\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1\right)Q_0^2 + 2\theta_1^2\theta_2\alpha_1\alpha_2 Q_0\tilde{\zeta}}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2}}{\dfrac{\theta_1\theta_2 {Q_0}^2}{\alpha_1\theta_2 + \alpha_2\theta_1}}$$

$$= \frac{\left(\alpha_1\theta_2 - \alpha_1\theta_1 + \alpha_2\theta_1\right)\left(\alpha_1\theta_2 + \alpha_2\theta_1\right)}{\theta_1^2\alpha_2^2 + \theta_1\theta_2\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2\theta_2^2}$$

$$= \frac{\left(\alpha_1 a - \alpha_1 + \alpha_2\right)\left(\alpha_1 a + \alpha_2\right)}{\alpha_2^2 + a\alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2 a^2} \ \left(a = \frac{\theta_2}{\theta_1}\right)$$

For $a = 1, \lim_{Q_0 \to \infty} \dfrac{TC^{ScreeningContractwithPrice}}{TC^{FirstBest}} = \dfrac{\left(\alpha_1 - \alpha_1 + \alpha_2\right)\left(\alpha_1 + \alpha_2\right)}{\alpha_2^2 + \alpha_1\left(\alpha_2 - \alpha_1\right) + \alpha_1^2} = 1$

3) $TC^{OptimalBaseline} \big/ TC^{FirstBest}$

$$\lim_{Q_0 \to \infty} \frac{TC^{OptimalBaseline}}{TC^{FirstBest}} = \begin{cases} \dfrac{\dfrac{\theta_1}{\alpha_1}Q_0^2}{\dfrac{\theta_1\theta_2 {Q_0}^2}{\alpha_1\theta_2 + \alpha_2\theta_1}} = \dfrac{\alpha_1\theta_2 + \alpha_2\theta_1}{\alpha_1\theta_2} = \dfrac{\alpha_1 a + \alpha_2}{\alpha_1 a} \ \forall a = \dfrac{\theta_2}{\theta_1} \geq \dfrac{\sqrt{\alpha_2^2 + \frac{1}{4}} + \frac{1}{2}}{\alpha_1} \\ \dfrac{\dfrac{\theta_1\theta_2[\left(2\theta_2 - \theta_1\right)\alpha_1 + \theta_1\alpha_2]Q_0^2}{(\theta_2\alpha_1 + \theta_1\alpha_2)^2} + \dfrac{2\alpha_1\theta_1\theta_2 Q_0\tilde{\zeta}}{\theta_2\alpha_1 + \theta_1\alpha_2}}{\dfrac{\theta_1\theta_2 {Q_0}^2}{\alpha_1\theta_2 + \alpha_2\theta_1}} = \dfrac{\left(2\theta_2 - \theta_1\right)\alpha_1 + \theta_1\alpha_2}{\alpha_1\theta_2 + \alpha_2\theta_1} = \dfrac{\left(2a - 1\right)\alpha_1 + \alpha_2}{\alpha_1 a + \alpha_2} \ \forall a = \dfrac{\theta_2}{\theta_1} < \dfrac{\sqrt{\alpha_2^2 + \frac{1}{4}} + \frac{1}{2}}{\alpha_1} \end{cases}$$

For $a = 1, \lim_{Q_0 \to \infty} \dfrac{TC^{OptimalBaseline}}{TC^{FirstBest}} = \dfrac{\left(2 - 1\right)\alpha_1 + \alpha_2}{\alpha_1 + \alpha_2} = 1$

4) $TC^{Uniform\,Price} \big/ TC^{FirstBest}$

$$\lim_{Q_0 \to \infty} \frac{TC^{UniformPrice}}{TC^{FirstBest}} = \lim_{Q_0 \to \infty} \frac{\dfrac{2\theta_1\theta_2}{\alpha_1\theta_2 + \alpha_2\theta_1}Q_0^2 + \dfrac{2\alpha_1\theta_1\theta_2}{\alpha_1\theta_2 + \alpha_2\theta_1}Q_0\tilde{\zeta}}{\dfrac{\theta_1\theta_2 {Q_0}^2}{\alpha_1\theta_2 + \alpha_2\theta_1}} = 2$$

5) $TC^{Baseline\_BusinessAsUsual} \big/ TC^{FirstBest}$

$$\lim_{Q_0\to\infty}\frac{TC^{Baseline\_BusinessAsUsual}}{TC^{FirstBest}}=\lim_{Q_0\to\infty}\frac{\frac{2\theta_1\theta_2}{\alpha_1\theta_2+\alpha_2\theta_1}Q_0^2-\frac{2\alpha_2\theta_1\theta_2}{\alpha_1\theta_2+\alpha_2\theta_1}Q_0\tilde{\zeta}}{\frac{\theta_1\theta_2{Q_0}^2}{\alpha_1\theta_2+\alpha_2\theta_1}}=2$$

C.4 Convergence as $\alpha_1\to 0$ and $\alpha_1\to 1$

Since we have

$TC^{FirstBest}\le TC^{ScreeningContractwithPriceandQuantity}\le TC^{ScreeningContractwithPrice}\le TC^{OptimalBaseline}$,

we only need to prove $TC^{OptimalBaseline}\to TC^{FirstBest}$ $as\ \alpha_1\to 0\ and\ \alpha_1\to 1$.

[Proof]

$$TC^{OptimalBaseline}=\begin{cases}\dfrac{\theta_1Q_0^2}{\alpha_1},\forall\dfrac{\theta_2}{\theta_1}\ge\dfrac{\sqrt{\alpha_2^2+\frac{1}{4}}+\frac{1}{2}}{\alpha_1}\\[2ex]\dfrac{\theta_1\theta_2[(2\theta_2-\theta_1)\alpha_1+\theta_1\alpha_2]Q_0^2}{(\theta_2\alpha_1+\theta_1\alpha_2)^2}+\dfrac{2\alpha_1\theta_1\theta_2Q_0\tilde{\zeta}}{\theta_2\alpha_1+\theta_1\alpha_2},otherwise\end{cases}$$

$$\lim_{\alpha_1\to 0}\frac{\sqrt{\alpha_2^2+\frac{1}{4}}+\frac{1}{2}}{\alpha_1}\to+\infty\Rightarrow TC^{OptimalBaseline}=\frac{\theta_1\theta_2[(2\theta_2-\theta_1)\alpha_1+\theta_1\alpha_2]Q_0^2}{(\theta_2\alpha_1+\theta_1\alpha_2)^2}+\frac{2\alpha_1\theta_1\theta_2Q_0\tilde{\zeta}}{\theta_2\alpha_1+\theta_1\alpha_2}$$

Then

$$\lim_{\alpha_1\to 0}\frac{TC^{OptimalBaseline}}{TC^{FirstBest}}=\frac{\frac{\theta_1\theta_2\left[(2\theta_2-\theta_1)\alpha_1+\theta_1\alpha_2\right]Q_0^2}{\left(\theta_2\alpha_1+\theta_1\alpha_2\right)^2}+\frac{2\alpha_1\theta_1\theta_2Q_0\tilde{\zeta}}{\theta_2\alpha_1+\theta_1\alpha_2}}{\frac{\theta_1\theta_2Q_0^2}{\theta_2\alpha_1+\theta_1\alpha_2}}=\frac{(2\theta_2-\theta_1)\alpha_1+\theta_1(1-\alpha_1)}{\theta_2\alpha_1+\theta_1(1-\alpha_1)}+2\alpha_1\tilde{\zeta}$$

$$\lim_{\alpha_1\to 1}\frac{\sqrt{\alpha_2^2+\frac{1}{4}}+\frac{1}{2}}{\alpha_1}\to 1\Rightarrow TC^{OptimalBaseline}=\frac{\theta_1}{\alpha_1}Q_0^2$$

Then

$$\lim_{\alpha_1 \to 1} \frac{TC^{OptimalBaseline}}{TC^{FirstBest}} = \frac{\frac{\theta_1}{\alpha_1} Q_0^2}{\frac{\theta_1 \theta_2 Q_0^2}{\theta_2 \alpha_1 + \theta_1 \alpha_2}} = \frac{\theta_2 \alpha_1}{\theta_2 \alpha_1 + \theta_1 \alpha_2} = 1$$

APPENDIX D

The Case with Continuous Distributed Producers

Set up and solve for the case in which the producers are continuously distributed. The total cost curves are:

$TC(\theta) = \beta(q-\theta)^2$, where the possibility density function of θ is $f(\theta)$ with $\theta \in [0, \bar{\theta}]$.

1. First-best Complete Information Case

$$\min_{(t(\theta), q(\theta))} \int_0^{\bar{\theta}} T(\theta) f(\theta) d\theta \qquad [D.1]$$

Subject to

$$T(\theta) = \beta(q(\theta)-\theta)^2 \qquad [D.2]$$

$$\int_0^{\bar{\theta}} \left(q(\theta)-\theta\right) f(\theta) d\theta = Q_0 \qquad [D.3]$$

Substitute [D.2] into [D.1], the problem can be simplified as:

$$\min_{q(\theta)} \int_0^{\bar{\theta}} \beta(q(\theta)-\theta)^2 f(\theta) d\theta \qquad [D.4]$$

Subject to

$$\int_0^{\bar{\theta}} \left(q(\theta)-\theta\right) f(\theta) d\theta = Q_0 . \qquad [D.5]$$

Then the Lagrangian function of the problem is:

$$L(\theta, q(\theta)) = \beta(q(\theta)-\theta)^2 f(\theta) + \lambda\left(q(\theta)-\theta\right) f(\theta)$$

Applying the Euler equation: $\frac{d}{d\theta}(\frac{\partial L}{\partial q(\theta)'}) - \frac{\partial L}{\partial q(\theta)} = 0$

$\frac{\partial L}{\partial q(\theta)'} = 0$ and $\frac{\partial L}{\partial q(\theta)} = f(\theta)[2\beta(q(\theta) - \theta) + \lambda]$

Therefore, $0 - f(\theta)[2\beta(q(\theta) - \theta) + \lambda] = 0 \Rightarrow q(\theta) - \theta = -\frac{\lambda}{2\beta}$. And substitute this into the problem and the solution can be found as follows:

$$q(\theta) = Q_0 + \theta$$

$$T(\theta) = \beta Q_0^2$$

$$TC = \beta Q_0^2$$

2. Screening Contract Methods

2.1 Screening Contract Method with Price and Quantity Specifications

Following the example in Laffont and Martimort (2002), we first derive the incentive compatible constraint. Denote the schedule of total payment and production quantity which is a function of θ as $(T(\theta), q(\theta))$. The decision problem for producer of type θ is to choose the pair of $(T(\tilde{\theta}), q(\tilde{\theta}))$ so as to maximize his profit (equation [D.6]):

$$\max_{\hat{\theta}} T(\hat{\theta}) - \beta(q(\hat{\theta}) - \theta)^2. \qquad [D.6]$$

For any producer to honestly announce its true type, it follows:

$$T(\theta) - \beta(q(\theta) - \theta)^2 \geq T(\theta') - \beta(q(\theta') - \theta)^2, \forall(\theta, \theta') \qquad [D.7]$$

$$T(\theta') - \beta(q(\theta') - \theta')^2 \geq T(\theta) - \beta(q(\theta) - \theta')^2, \forall(\theta, \theta'). \qquad [D.8]$$

Adding [D.7] and [D.8], we obtain:

$$\left(\theta' - \theta\right)\left(q\left(\theta'\right) - q\left(\theta\right)\right) \geq 0 \,. \qquad \text{[D.9]}$$

Incentive compatibility alone requires that *q(θ)* is non-decreasing in θ. *T* implies that *q(·)* and *t(·)* are differentiable almost everywhere. With differentiability, we can further derive that for the producers to honestly announce its true type, *(T(θ), q(θ))* satisfies:

$$\left.\frac{\partial T(\hat{\theta})}{\partial \hat{\theta}}\right|_{\hat{\theta}=\theta} - 2\beta\left(q\left(\hat{\theta}\right) - \theta\right)\left.\frac{\partial q\left(\hat{\theta}\right)}{\partial \hat{\theta}}\right|_{\hat{\theta}=\theta} = 0 \,. \qquad \text{[D.10]}$$

Equation [D.10] is the first order condition of profit maximization decision of producer of type θ, which is also the incentive compatible constraint of the regulator's problem. Rewrite [D.10] as follows:

$$T'(\theta) - 2\beta\left(q\left(\theta\right) - \theta\right)q'(\theta) = 0 \qquad \text{[D.11]}$$

Then the regulator's problem can be formulated as follow:

$$\min_{(t(\theta),q(\theta))} \int_0^{\bar{\theta}} T\left(\theta\right) f\left(\theta\right) d\theta \qquad \text{[D.12]}$$

Subject to

$$T'(\theta) - 2\beta\left(q\left(\theta\right) - \theta\right)q'(\theta) = 0 \qquad \text{[D.13]}$$

$$T\left(\theta\right) - \beta(q\left(\theta\right) - \theta)^2 \geq 0 \qquad \text{[D.14]}$$

$$T\left(0\right) - \beta(q\left(0\right) - 0)^2 = 0 \qquad \text{[D.15]}$$

$$\int_0^{\bar{\theta}} \left(q(\theta)-\theta\right) f(\theta) d\theta = Q_0 \quad \text{[D.16]}$$

The problem is easier to solve by defining: $u(\theta)=T(\theta)-\beta(q(\theta)-\theta)^2$. Then we have $T(\theta)=u(\theta)+\beta(q(\theta)-\theta)^2$. And the problem can be rewritten as follow:

$$\min_{(u(\theta),q(\theta))} \int_0^{\bar{\theta}} [u(\theta)+\beta(q(\theta)-\theta)^2] f(\theta) d\theta \quad \text{[D.17]}$$

Subject to

$$u'(\theta)=T'(\theta)-2\beta\left(q(\theta)-\theta\right)(q'(\theta)-1)=2\beta\left(q(\theta)-\theta\right) \quad \text{[D.18]}$$

$$u(\theta)\geq 0 \quad \text{[D.19]}$$

$$u(0)=0 \quad \text{[D.20]}$$

$$\int_0^{\bar{\theta}} \left(q(\theta)-\theta\right) f(\theta) d\theta = Q_0 \quad \text{[D.21]}$$

Therefore,

$$u(\theta)=u(0)+\int_0^{\theta} u'(\eta)d\eta=\int_0^{\theta} 2\beta\left(q(\eta)-\eta\right)d\eta=2\beta\int_0^{\theta} q(\eta)d\eta-\beta\theta^2 \quad \text{[D.22]}$$

The problem can be simplified as follow:

$$\min_{q(\theta)} \int_0^{\bar{\theta}} [2\beta\int_0^{\theta} q(\eta)d\eta-\beta\theta^2+\beta(q(\theta)-\theta)^2] f(\theta)d\theta=\beta\int_0^{\bar{\theta}} [\frac{2\left(1-F(\theta)\right)}{f(\theta)} q(\theta)-\theta^2+(q(\theta)-\theta)^2] f(\theta)d\theta$$

[D.23]

Subject to

$$\int_0^{\bar{\theta}} \left(q(\theta)-\theta\right) f(\theta) d\theta = Q_0 \quad \text{[D.24]}$$

The solution is:

$$q(\theta) = Q_0 + \int_0^{\bar{\theta}} (1 - F(\theta))d\theta - \frac{1 - F(\theta)}{f(\theta)} + \theta$$

$$u(\theta) = 2\beta\theta\left[Q_0 + \int_0^{\bar{\theta}} \left(1 - F(\theta)\right) d\theta \right] - 2\beta\int_0^{\theta} \frac{1 - F(\eta)}{f(\eta)} d\eta$$

$$T(\theta) = 2\beta\theta\left[Q_0 + \int_0^{\bar{\theta}} \left(1 - F(\theta)\right) d\theta \right] - 2\beta\int_0^{\theta} \frac{1 - F(\eta)}{f(\eta)} d\eta + \beta(Q_0 + \int_0^{\bar{\theta}} (1 - F(\theta))d\theta - \frac{1 - F(\theta)}{f(\theta)})^2$$

$$TC = \beta\left[Q_0 + \int_0^{\bar{\theta}} \left(1 - F(\theta)\right) d\theta \right]^2 - \beta\int_0^{\bar{\theta}} \left[\frac{1 - F(\theta)}{f(\theta)} \right]^2 f(\theta)d\theta$$

If θ follows uniform distribution, then $f(\theta) = \frac{1}{\bar{\theta}}$ and $F(\theta) = \frac{\theta}{\bar{\theta}}$. And

$$q(\theta) = Q_0 - \frac{\bar{\theta}}{2} + 2\theta$$

$$u(\theta) = \beta(2\theta Q_0 - \bar{\theta}\theta + \theta^2)$$

$$T(\theta) = \beta[\left(Q_0 - \frac{\bar{\theta}}{2} + 2\theta \right)^2 - 2\theta^2]$$

$$TC = \beta(Q_0^2 + Q_0\bar{\theta} - \frac{\bar{\theta}^2}{12})$$

2.2 Screening Contract Method with Price Specification Only

Again, we first derive the incentive compatible constraint. Denote the schedule of unit payment and lump sum transfer which is a function of θ as $(t(\theta), S(\theta))$. The decision problem for producer of type θ is to choose the pair of $(t(\hat{\theta}), S(\hat{\theta}))$ (and determine the production quantity) so as to maximize his profit (Equation [D.25]):

$$\max_{t(\hat{\theta})} q(\hat{\theta})t(\hat{\theta}) - S(\hat{\theta}) - \beta\left(q(\hat{\theta}) - \theta\right)^2, where\ 2\beta\left(q(\hat{\theta}) - \theta\right) = t(\hat{\theta})$$
$$\Rightarrow \max_{t(\hat{\theta})} \left(\frac{t(\hat{\theta})}{2\beta} + \theta\right)t(\hat{\theta}) - S(\hat{\theta}) - \beta\left(\frac{t(\hat{\theta})}{2\beta} + \theta - \theta\right)^2 . \qquad [D.25]$$

For the producers to honestly announce its true type, *(t(θ), S(θ))* satisfies:

$$\frac{t(\hat{\theta})}{2\beta}\frac{\partial t(\hat{\theta})}{\partial \hat{\theta}}\bigg|_{\hat{\theta}=\theta} + \theta\frac{\partial t(\hat{\theta})}{\partial \hat{\theta}}\bigg|_{\hat{\theta}=\theta} - \frac{\partial S(\hat{\theta})}{\partial \hat{\theta}}\bigg|_{\hat{\theta}=\theta} = 0 . \qquad [D.26]$$

Equation [D.26] is the first order condition of profit maximization decision of producer of type θ, which is also the incentive compatible constraint of the regulator's problem. Rewrite [D.26] as follows:

$$\frac{t(\theta)}{2\beta}t'(\theta) + \theta t'(\theta) - S'(\theta) = 0 . \qquad [D.27]$$

Then the regulator's problem can be formulated as follow:

$$\min_{(t(\theta),S(\theta))} \int_0^{\bar{\theta}} [q(\theta)t(\theta) - S(\theta)] f(\theta)d\theta \qquad [D.28]$$

Subject to

$$\frac{t(\theta)}{2\beta}t'(\theta) + \theta t'(\theta) - S'(\theta) = 0 \qquad [D.29]$$

$$q(\theta)t(\theta) - S(\theta) - \beta(q(\theta) - \theta)^2 \geq 0 \qquad [D.30]$$

$$t(0)q(0) - S(0) - \beta q(0)^2 = 0 \qquad [D.31]$$

$$\int_0^{\bar{\theta}} \left(q(\theta) - \theta\right) f(\theta)d\theta = Q_0 \qquad [D.32]$$

$$2\beta\left(q(\theta) - \theta\right) = t(\theta) \qquad [D.33]$$

Substitute $q(\theta)$ as a function of $t(\theta)$, then the problem can be rewritten as follow:

$$\min_{(t(\theta),S(\theta))} \int_0^{\bar{\theta}} [\frac{t(\theta)^2}{2\beta} + \theta t(\theta) - S(\theta)] f(\theta) d\theta \qquad \text{[D.34]}$$

Subject to

$$\frac{t(\theta)}{2\beta} t'(\theta) + \theta t'(\theta) - S'(\theta) = 0 \qquad \text{[D.35]}$$

$$\frac{t(\theta)^2}{2\beta} + \theta t(\theta) - S(\theta) - \beta(\frac{t(\theta)}{2\beta})^2 \geq 0 \qquad \text{[D.36]}$$

$$\frac{t(0)^2}{4\beta} - S(0) = 0 \qquad \text{[D.37]}$$

$$\int_0^{\bar{\theta}} \left(\frac{t(\theta)}{2\beta} \right) f(\theta) d\theta = Q_0 . \qquad \text{[D.38]}$$

First minimize [D.34] with constraint [D.35] and [D.38]. Then the Lagrangian function is:

$$L = [\frac{t(\theta)^2}{2\beta} + \theta t(\theta) - S(\theta)] f(\theta) + \lambda [\frac{t(\theta)}{2\beta} t'(\theta) + \theta t'(\theta) - S'(\theta)] + \mu [\left(\frac{t(\theta)}{2\beta} \right) f(\theta)] \qquad \text{[D.39]}$$

Then the two Euler equations are:

$$\frac{d}{d\theta}\left(\frac{\partial L}{\partial t'} \right) - \frac{\partial L}{\partial t} = \frac{t(\theta)}{2\beta}\lambda' + \frac{\lambda}{2\beta} t'(\theta) + \theta\lambda' + \lambda - \left(\frac{t(\theta)}{\beta} + \theta \right) f(\theta) - \frac{\lambda}{2\beta} t'(\theta) - \frac{\mu f(\theta)}{2\beta} = 0 \qquad \text{[D.40]}$$

$$\frac{d}{d\theta}\left(\frac{\partial L}{\partial S'} \right) - \frac{\partial L}{\partial s} = -\lambda' + f(\theta) = 0 \qquad \text{[D.41]}$$

Then, we obtain

$$\lambda(\theta) = \frac{t(\theta) f(\theta)}{2\beta} + \frac{\mu f(\theta)}{2\beta} \qquad \text{[D.42]}$$

$$\lambda'(\theta) = f(\theta) \quad [D.43]$$

Therefore,

$$t'(\theta) = 2\beta - \frac{(t(\theta) - \mu)f'(\theta)}{f(\theta)} . \quad [D.44]$$

Equation [D.44] suggests that to get an analytical solution for the problem, the distribution of θ needs to be known. If θ follows uniform distribution, then $f(\theta) = \frac{1}{\bar{\theta}}$ and $F(\theta) = \frac{\theta}{\bar{\theta}}$. Then

$$t'(\theta) = 2\beta . \quad [D.45]$$

The solution is:

$$t(\theta) = 2\beta(Q_0 - \frac{\bar{\theta}}{2} + \theta)$$

$$S(\theta) = \beta\left(Q_0 - \frac{\bar{\theta}}{2}\right)^2 + 2\beta\theta(Q_0 - \frac{\bar{\theta}}{2} + \theta)$$

$$TC = \beta(Q_0^2 + Q_0\bar{\theta} - \frac{\bar{\theta}^2}{12})$$

3. Uniform Price Method

The regulator's problem can be formulated as follow:

$$\min_{(t,q(\theta))} \int_0^{\bar{\theta}} tq(\theta)f(\theta)d\theta \quad [D.46]$$

Subject to

$$2\beta(q(\theta) - \theta) = t \quad [D.47]$$

$$\int_0^{\bar{\theta}} \left(q(\theta)-\theta\right) f(\theta) d\theta = Q_0 \quad \text{[D.48]}$$

The solution is:

$$q(\theta) = Q_0 + \theta$$

$$t = 2\beta Q_0$$

$$TC = 2\beta Q_0^2 + 2\beta Q_0 \int_0^{\bar{\theta}} \theta f(\theta) d\theta$$

If θ follows uniform distribution, then $f(\theta) = \frac{1}{\bar{\theta}}$ and $F(\theta) = \frac{\theta}{\bar{\theta}}$. And

$$TC = \beta(2Q_0^2 + Q_0\bar{\theta}).$$

4. Optimal Baseline Method

Again, the regulator needs to decide whether to leave some high costs producers out of the program. Let $\hat{Q}$ and t denote the baseline and unit payment determined by the regulator. Then let q_{low} and θ_{low} denote the production quantity and additionality parameter for the active producers with highest costs:

$$\beta(q_{low} - \theta_{low})^2 = t(q_{low} - \hat{Q}) \quad \text{[D.49]}$$

Therefore,

$$\theta_{low} = \hat{Q} - \frac{t}{4\beta}.$$

Then the regulator's problem can be formulated as follow:

$$\min_{(\hat{Q},t)} \int_{\hat{Q}-\frac{t}{4\beta}}^{\bar{\theta}} t(q(\theta) - \hat{Q}) f(\theta) d\theta \quad \text{[D.50]}$$

Subject to

$$2\beta\left(q\left(\theta\right)-\theta\right)=t \quad [D.51]$$

$$\int_{\hat{Q}-\frac{t}{4\beta}}^{\bar{\theta}}(q\left(\theta\right)-\theta)f\left(\theta\right)d\theta \quad [D.52]$$

$$\hat{Q}-\frac{t}{4\beta}\geq 0 \quad [D.53]$$

Solution

$$q\left(\theta\right)=\begin{cases}\theta+\sqrt{Q_0\bar{\theta}},\forall Q_0<\bar{\theta}\\ \theta+Q_0,\forall Q_0\geq\bar{\theta}\end{cases}$$

$$t=\begin{cases}2\beta\sqrt{Q_0\bar{\theta}},\forall Q_0<\bar{\theta}\\ 2\beta Q_0,\forall Q_0\geq\bar{\theta}\end{cases}$$

$$\hat{Q}=\begin{cases}\bar{\theta}-\frac{\sqrt{Q_0\bar{\theta}}}{2},\forall Q_0<\bar{\theta}\\ \frac{Q_0}{2},\forall Q_0\geq\bar{\theta}\,?\end{cases}$$

$$TC=\begin{cases}2\beta Q_0^{3/2}\sqrt{\bar{\theta}},\forall Q_0<\bar{\theta}\\ \beta Q_0^2+2\beta Q_0\int_0^{\bar{\theta}}\theta f(\theta)d\theta,\forall Q_0\geq\bar{\theta}\end{cases}$$

If θ follows uniform distribution, then $f\left(\theta\right)=\frac{1}{\bar{\theta}}$ and $F\left(\theta\right)=\frac{\theta}{\bar{\theta}}$. And

$$TC=\begin{cases}2\beta Q_0^{3/2}\sqrt{\bar{\theta}},\forall Q_0<\bar{\theta}\\ \beta Q_0^2+\beta Q_0\bar{\theta},\forall Q_0\geq\bar{\theta}\end{cases}$$

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