VOLUNTARY CARBON MARKET PARTICIPATION AND UNINTENDED CONSEQUENCES: AN ECONOMIC ANALYSIS

A Thesis

by

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ABSTRACT

Agricultural activities account for nearly a quarter of anthropogenic greenhouse gas (GHG) emissions mainly from deforestation and livestock, soil and nutrient management. Also it is the biggest emitter of non-carbon dioxide GHGs. Meanwhile farmers typically face more than one production possibility and they typically produce varying amounts of net GHG emissions at different costs. Therefore GHG emission reductions may be achieved by providing incentives for farmers to adopt alternative production activities. Intuitively, total GHG emissions will decrease after adopting lower emitting practices. However certain incentive designs might lead to GHG net emission increases or lower than expected reductions, hence unintended consequences. Here, two major forms of carbon market program are investigated for their effects on net GHG emissions and the conditions under which the unintended consequences occur are examined analytically. This model shows for net emitters the program design can lead to increased emissions – the rebound effect. While for negative emitters (those sequestering or offsetting emissions through bioenergy), the program results in trivial emission reductions. We also find that it is desirable to alter program design to limit participation to baseline levels for those who emit and to encourage participation well beyond baseline levels for those who generate negative emissions.

DEDICATION

To Xi, for everything we have been through.

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NOMENCLATURE

GHG	Greenhouse Gas covering the 6 gasses in Kyoto Protocol – carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride
CO_2	Carbon Dioxide
Non-CO_2	Non Carbon Dioxide
CH_4	Methane
N_2O	Nitrous Oxide
EPA	Environmental Protection Agency
ERS USDA	Economic Research Service United States Department of Agriculture
UNFCCC	United Nations Framework Convention on Climate Change
IPCC	Intergovernmental Panel on Climate Change
INDCs	Intended Nationally Determined Contributions
ITMOs	Internationally Transferred Mitigation Outcomes
CARB	California Air Resources Board
EIA	Energy Information Administration

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1. INTRODUCTION

Establishing carbon markets is a widely discussed and, in cases, a widely implemented economic approach to reducing greenhouse gas (GHG) emissions, certainly since its mention at the Kyoto Protocol (UNFCCC 1997). “Carbon market” is the widely used generic name for a carbon-equivalent market covering the Kyoto GHGs of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. A carbon market will generally reward producers who can lower their emissions or increase their negative contribution to emissions, favoring those with low implementation costs, and will reflect the cost of emissions reductions across the economy. In the agricultural sector, farmers generally face production alternatives that alter GHG emissions at a cost (McCarl and Schneider, 2000). Therefore, a carbon market can provide incentives for farmers to adopt less-net emissions-intensive practices. Theoretically, this would cause a reduction in total agricultural net carbon equivalent emissions.

However, it is possible that in the face of incentives (depending on incentive design), adverse results might appear, with emissions increasing due to leakage (Searchinger et al, 2008, Fargione et al, 2008) or production increases. This counterintuitive consequence is referred to in the energy sector as the “rebound effect” (Gillingham et al, 2015). Additionally program design may reduce incentives for sequestration activities or those providing lower emitting substitute products like biomass feedstocks for bioenergy.

Carbon markets have been controversial, with much negative attention occurring around the time of the Waxman Markey bill consideration (U.S. Congress 2009). In turn, many in the U.S. government have considered alternatives to a mandatory market in the form of voluntary programs (Price, 2005). One such voluntary program, developed based on current practices, would pay an incentive for a net reduction in emissions per acre, per animal emission, or per other unit as for example under the California rice protocol (CARB 2015a). We investigate this prospect herein and look at whether unintended consequences could be a problem, as well as investigate ways that policy design may be adopted to preclude it.

More specifically, we will examine the adoption of net emissions-reducing and sequestration-enhancing practices in a theoretical carbon market where an incentive is paid for net reductions generated in agriculture. Furthermore, we will examine the performance of such a market under mandatory enrollment and voluntary enrollment. In the mandatory market setting, we will examine payments based on the total carbon offset amount. In the voluntary market setup, we look at payment for the difference between newly adopted practice and the practice used in the absence of a market. Each participation type (mandatory vs. voluntary) and associated incentive form will be examined in terms of net GHG emission offset amount. In the analysis, we will derive analytical conditions under which unintended consequences will occur and then explore market design elements that prevent such effects. We will also illustrate the findings in an empirical model.

The objective of this effort is to study cases where the voluntary market either worsens emissions or dampens emissions reductions compared to the mandatory market. This will be done by developing a simple economic model of the adoption of emissions-reducing or offset/sequestration-enhancing strategies under voluntary and mandatory participation. And then within that model we will find conditions under which either the net emissions effect is dampened or can even turn into increases in a voluntary as opposed to a mandatory market. Finally, suggestions will be made on program design elements to avoid these problems.

The rest of this paper is structured as follows. Section 2 discusses the background of market forms and agricultural mitigation opportunities. Section 3 reviews the literature on economic incentives and GHG mitigation. Section 4 develops an economic model that will be used to study the conditions that cause lower emissions reductions (and even possibly increases) along with decreasing the incentives for participation for negative emitters. Section 4 also presents potential program design elements that can improve the net emissions implications. Section 5 uses a simple mathematical programming model to empirically illustrate the findings. Section 6 discusses outcomes from the model and draws conclusions.

2. BACKGROUND

Agriculture can pursue a number of alternative practices that permit net emissions reductions. For the most part, these practices are already well known, but they are used to a limited extent because they cost more than current practices, meaning farmers need incentives to adopt them (Antle and McCarl, 2003).

One way that could be used to implement economic incentives involves establishing a carbon market that allows those with high cost emissions reductions potential to purchase offsets from others who have lower cost emissions reductions or sequestration enhancement opportunities (IPCC 2014). In turn, it has been widely argued that this would result in agricultural producers receiving some form of payment incentive to reduce their emissions (Millar et al, 2010).

The basic form of carbon market studied here is one that results in a price being offered for net agricultural emissions reductions. This price reflects the value that society places on reducing carbon emissions. In establishing the eligibility of strategies for payment, one important concept is additionality. In particular, in the Kyoto Protocol, the set goal is that the net emissions reductions paid for in a market should be additional to any that arise in the absence of the market. This means that net emissions-reducing practices that would be in place in the absence of a market are not eligible for payment. The payment is only for net emissions reductions that fall below a baseline amount.

Two market forms will be used to reflect this baseline offset. Within the mandatory market, it is assumed that the emissions profile in the absence of the market is observed and imposed as a baseline amount. In turn, any net emissions below that amount will be rewarded, while emissions above that amount will be penalized. In our modeling structure, we will impose a fixed baseline amount where we set the baseline amount as the total emissions from all sources in the absence of a program and will only pay for net emissions less than that amount.

The second market form is a voluntary market. Under this form, net emissions reducers are required to do better than a norm for the region. If a farmer is producing rice under a mitigated rice production practice, the program will only pay for the increment that emissions using the new practice are less than the emissions from the common practices used for rice production in the absence of a market (hereafter called baseline practices). In this case, the GHG net emissions reductions eligible amount for payment is the emissions under the new practice minus the emissions under the baseline. Therefore, we need to form a baseline norm on a per-acre-of-rice basis, per unit of biofuel, per ton of manure, or per animal, depending on the enterprise. Then, the amount of money farmers receive will be the emissions rate under the improved practice minus the emissions rate under the baseline practice.

Emissions under the mandatory program within the scope of the project area cannot exceed the emissions in the baseline because the extra production will be penalized. Naturally, this ignores leakage when the program only covers part of the globe and activities within the project area cause a production shift outside the area (see discussion in Murray et al, 2004). However, this is not the case under the voluntary program. In particular, if the payment from the program is high enough, it would increase the amount of production under the net-emissions-reducing strategy. When the production level is well in excess of the amount produced in the baseline, the emissions per acre goes down, but the emissions in total can go up due to the expansion in production. This will be an outcome in our analytical model below for certain cases.

There is also a possibility that the voluntary program will reduce incentives for negative emissions possibilities, like sequestration and bioenergy offsets. In particular, the current adoption of things like bioenergy for electricity production and afforestation is at relatively low levels. The voluntary program would pay for bioenergy emissions savings relative to the norm of bioenergy offsets in the region, and for sequestration the program would offer payment relative to the norm for say forest or tillage management in the region. Under the mandatory program, it would pay for the net emissions reductions from sequestration to the extent that it is less than the total amount sequestered in the baseline. This is a fixed number for the mandatory case and a per-acre amount for the voluntary program. Therefore, the voluntary program may not provide enough incentives to greatly expand the acreage to achieve greater net reductions from bioenergy or sequestration. This can limit the potential of the voluntary program to stimulate expansion of negative emitting strategies. This will also be explored in the analytical model.

2.1 Background on Carbon Programs

Carbon programs to encourage mitigation activities are the subject of recent policy actions. The Paris Agreement (UNFCCC 2015) is an agreement that may lead to global carbon markets. The U.S. Clean Power Plan, which was recently finalized by the

Environmental Protection Agency (EPA), is a national carbon program focused on the electrical energy generating sector (U.S. EPA 2015) and may also cause markets to form. The cap-and-trade program in California is a state program that sets an emissions limit and covers 85% of state GHGs (CARB 2014) and offers a voluntary market. Here we will generally discuss these three programs.

The recent Paris Agreement is a legally binding and universal agreement on climate mitigation through net GHG emissions reductions. As of now, it covers 96% of global emissions. It sets out a global action goal that aims to hold the global average temperature increase below 2°C above pre-industrial levels and to pursue efforts to limit it to 1.5°C. Countries that are parties to the agreement have submitted statements on actions their reductions aims in the form of Intended Nationally Determined Contributions (INDCs) that are available through UNFCCC (UNFCCC 2015). In its INDC, China committed to peak its CO_2 emissions around 2030 and reduce its CO_2 emissions per unit of GDP by 60 to 65% from the 2005 level by then. The U.S. INDC indicates that it intends to reduce its GHG emissions by 26 to 28% from the 2005 level by 2025. All the INDCs are to be updated every five years, becoming successively more ambitious. However, the Paris Agreement does not mention a binding enforcement mechanism to be triggered when a country fails to meet its INDC. Internationally Transferred Mitigation Outcomes (ITMOs) is another new terminology adopted in the agreement which stands for “internationally transferred mitigation outcomes”. The provision for ITMOs provides an international policy linkage which covers not only cap-and-trade programs but also other nation mitigation policies. The use of ITMOs need to promote environmental integrity and avoid double counting. The establishment of the international carbon market and markets for other tradable mitigation outcomes can be achieved through ITMOs in the future. The agreement also emphasized the importance of international market mechanism in enlarging mitigation potentials and achieving mitigation goals.

The U.S. Clean Power Plan provides emissions reduction goals for existing, modified, and reconstructed power plants, which together account for almost 40% of U.S. CO_2 emissions (U.S. EIA 2013). States are also required to develop their own plans to achieve these emissions reduction goals. The reduction goals are to be achieved through fuel switching, carbon market trading programs, increasing energy efficiency, retrofits, investing in renewable energy, and so on. The trading program can be designed based on either emissions rate (pounds of CO_2 per megawatt hour) or emissions amount (tons of CO_2). Under the rate-based trading system, power plants can trade emissions with other electricity resources to meet their assigned rate. Under the mass-based trading system, the EPA will distribute the allowances, which can be traded on the open market. This plan also covers pollutant precursors like sulfur dioxide (SO_2) and N_2O.

The California cap-and-trade program is an essential part of California's climate plan (CARB 2014), which aims to return to 1990 levels of GHG emissions by 2020. As mentioned in CARB (2014), the trading system started to allocate the caps for electricity generators in 2013 at 2% below their emissions levels in 2012. The distributers of transportation fuels, natural gas, and other fuels received their compliance obligations in 2015. All caps declined 2% in 2014 and will decline 3% annually from 2015 to 2020.

Companies can enter a carbon market purchasing emissions rights from other emitting entities in order to meet their emissions obligation or can buy agricultural offsets. Agricultural offsets that are allowed have established protocols. Currently there are protocols for forest (CARB 2015b), animal manure treatment plus a recently proposed one for rice cultivation (CARB 2015a) that provides rice famers an opportunity to trade their credits earned from adopting GHG emission reducing practices.

2.2 Background on Agricultural Mitigation Potential

McCarl and Schneider (2000) argued there are three ways agriculture may participate in a carbon market. First, agriculture production has substantial GHG emissions, and farmers may adopt alternative management practices to reduce emissions of methane, nitrous oxide, and carbon dioxide. Second, agriculture may enhance its sequestration of atmospheric carbon dioxide by storing it in soils or standing vegetation (mainly trees). Third, agriculture may produce products that displace consumption of emissions-intensive products (mainly fossil fuels) and thus reduce emissions from those products.

Each of these ways is discussed below with literature citations and indications of how they might interact in a voluntary or mandatory market.

2.2.1 Source of emissions

Agriculture, forestry, and land use change contribute significantly to GHG emissions (estimated at 24% of total global anthropogenic GHG emissions, IPCC 2014). The agricultural sector is the biggest non-CO_2 emitter, accounting for an estimated 56% of global non-CO_2 emissions in 2005 (U.S. EPA 2011). Within the agricultural sector, paddy rice cultivation, manure management, and enteric fermentation are major sources of methane (CH_4) emissions; fertilization and manure are major sources of nitrous oxide (N_2O) emissions.

Net emissions reductions can be achieved by adopting alternative farming practices (see discussion in McCarl and Schneider, 2000, 2001, Smith et al, 2008, IPCC 2014).

2.2.1.1 Carbon dioxide

Contributions from agriculture across countries vary substantially, with large differences existing between tropical developing countries and developed countries with commercial agriculture. Deforestation and land degradation are two major sources of agricultural GHG emissions in developing countries, amounting to 17% of total GHG emissions in 2004 (IPCC 2007). The CO_2 emitted from agricultural annual strategies (except that from deforestation) is considered neutral since it was absorbed during the year through photosynthesis and will thus is not treated here.

Agricultural GHG emissions in developed countries are mainly caused by fossil fuel usage in production for tractors, irrigation pumping, and grain drying, among other sources, as well as by reductions in soil carbon through use of intense tillage or plowing grasslands.

Reducing such emissions sources involves reducing use of tillage, agricultural machinery, and irrigation pumps; indirect emission reductions from production of fertilizers, needed transportation, and other inputs; and enhanced energy efficiency.

2.2.1.2 Methane

Agricultural methane emissions largely involve rice cultivation, animal enteric fermentation, and manure management. For managing rice emissions, IPCC (2007) indicated that draining wetland rice during the growing season reduces the CH_4 emissions. Other strategies include altering cultivars, improving offseason water management, keeping soil as dry as possible, increasing rice production per acre to enhance and reduce needed acres, adjusting the timing of organic residue additions, composting residues before incorporation, and producing biogas from residues before incorporation.

Livestock management strategies also affect GHG emissions. Livestock operations emit about one-third of global anthropogenic methane emissions, with the primary vehicles being enteric fermentation and manure. For enteric fermentation, IPCC (2007) indicated that practices for reducing emissions from this source can be divided into three categories: improved feeding practices, adopting specific dietary additives, increasing productivity so less animals or shorter lifetimes are needed, and animal breeding.

In terms of manure management, animal manures release significant amounts of non-CO_2 GHGs, included N_2O and CH_4, during storage, but the emissions amount changes by manure handling system. Mitigation activities involve cooling, use of solid covers, mechanically separating solids from slurry, capturing emitted methane, using anaerobic digestion, handling manures in solid form, covering manure heaps, and altering feeding practices.

2.2.1.3 Nitrous oxide

Nitrogen applied in fertilizers and manure, along with other sources, including fixation by legumes, are collectively a source of N_2O emissions because plants generally do not capture all of the applied nitrogen. Mitigation strategies involve reducing leaching and volatilization losses, adjusting application rates based on precision farming, using slow or controlled-release fertilizer, using nitrification inhibitors, and avoiding excess nitrogen applications.

2.2.2 Sequestration

The second way to reduce agricultural GHG emissions is to increase carbon storage in the ecosystem. Every year carbon dioxide is absorbed from the atmosphere through photosynthesis and the carbon is stored in plants, but it is then released when the plants die. Sequestration can be enhanced by increasing retention of this material by enhancing roots, surface litter, or standing perennials like trees. Consequently, the inventory held in the soil or in standing vegetation can be increased in order to achieve a greater amount of sequestered carbon. This strategy is commonly mentioned as carbon sequestration. Carbon sequestration in terms of agriculture will be discussed in two forms: soil sequestration and standing vegetation.

2.2.2.1 Soil sequestration

Currently, U.S. agricultural soils hold eight billion metric tons of carbon (Kimble et al, 2002). Management practices that reduce soil disturbance generally result in more sequestered carbon. As mentioned in Lewandrowski et al. (2004), this includes residue management, less intensive tillage systems, increased use of winter cover strategies and perennials, altered forest harvest practices, land conversion to grasslands or forest, and restoration of degraded soils.

There is also the possibility of enhancing soil carbon sequestration through the application of biochar (discussed in McCarl et al, 2009).

2.2.2.2 Standing vegetation sequestration

Standing perennials hold a significant portion of carbon. For example, carbon constitutes approximately 50% of the dry mass of trees. Generally one accounts for carbon in standing vegetation that exists for more than one year. Vegetation that holds carbon for less than one year is not considered because on an annual basis it absorbs and releases the carbon. Thus, one strategy is to increase the inventory of standing trees, which also reduces soil disturbance and increases the inventory of carbon in the local soils.

2.2.3 Providing substitute products

The third way that agriculture could be involved in reducing net emissions involves providing substitutes for products whose usage causes substantial emissions. This involves growing specialized commodities or utilizing existing agricultural commodities as biomass feedstocks for bioenergy that replaces fossil fuel usage. It also includes increasing substitution of wood and other agricultural products for more GHG-intensive building materials.

2.2.3.1 Biomass for bioenergy

Fossil fuels used in electrical generation or for liquid fuels can be substituted by agricultural products. In a power plant, it is possible to burn agricultural biomass in the form of crop residues, energy strategies, or manure, among others to offset fossil fuel use. Burning biomass instead of fossil fuel would reduce net CO_2 concentration into the atmosphere because of the photosynthetic process: about 95% of CO_2 emitted when burning the biomass would be removed from the atmosphere during plant growth, meaning the carbon is being recycled (McCarl 2008b). It seems like a carbon-neutral process, but one must also consider the emissions from biomass production and transportation from field to electrical generation facility. EPA biogenic carbon documents discuss this (U.S. EPA 2011) and provide offset estimates, as does McCarl (2008a).

Liquid fuel substitution is also possible by taking agricultural commodities and transforming them into conventional or cellulosic ethanol plus biodiesel, along with other possible energy forms like butanol. Again, this would create a carbon recycling process due to the carbon uptake during biomass growth. But one needs to go through the full production cycle using concepts like lifecycle assessment, as discussed in McCarl (2008b).

2.2.3.2 Building products substitution

According to the U.S. Department of Energy, buildings are responsible for 38% of carbon emissions. One can also employ an increased use of biomass products like wood in construction to offset emissions-intensive construction materials like concrete block or steel. Gustavsson et al. (2006) compared the CO_2 emissions from wood-framed and concrete-framed buildings and showed that wood-framed construction involves less

GHG emissions and energy consumption. This benefit results from different emissions in production, transportation, and waste recovery of spent building materials.

3. LITERATURE REVIEW

Numerous policies have been suggested to enhance GHG mitigation through participation by the agricultural sector (Smith et al, 2008). A review of existing offset programs was provided by Kollmuss et al. (2010).

Smith et al. (2008) covered almost every mitigation option in agriculture and estimated their mitigation potentials. Water and rice management are important mitigation options. The mitigation practices of rice cultivation are discussed in detail. This paper also indicated that mitigation and adaptation may happen at the same time and interact with each other.

McCarl and Schneider (2000) mentioned that markets for emissions trading should be an option when endeavoring to reduce GHG emissions. The results of reduction efforts remain uncertain; meanwhile, the potential negative externalities of policies include deforestation, additional use of pesticides, and competition with food and fiber production.

Lobell et al. (2013) investigated investment in agriculture technologies and its climate-related co-benefits. They argued that the broad-based efforts to adapt agriculture to climate change can have mitigation co-benefits that are inexpensive relative to many mitigation-focused activities. Therefore, the programs and funds that support adaptation should not be treated as completely separate from mitigation ones.

Smith et al. (2007) investigated the constraints and barriers faced by mitigation policies in agriculture. The barriers they discussed were permanence, additionality, uncertainty, and leakage. Based on these issues, the actual level of GHG mitigation is far below the theoretical expectation.

Lutsey and Sperling (2008) focused on regional mitigation policies and their effect on national emissions goals. Their paper argued that sub-national action should dominate since local governments are more responsible and knowledgeable about local environment. They indicated that cooperation and interaction between sub-national governments on mitigation policies would be helpful for us to understand the worldwide emissions market. But whether the global emissions market will evolve or not is still uncertain.

Antle and McCarl (2003) discussed incentive design of mitigation policies. Direct government payment and private market are two alternative options for incentive. For soil carbon sequestration programs, if government provides the incentive based on numbers of hectare, then extra monitoring cost needs to be considered. If the payment is provided based on the amount of carbon mitigated, additional studies on soil carbon status are crucial to the program. The spatial heterogeneity will diminish the policy efficiency if the payment is designed based on only the activities. On the other side, the payment mechanism based on amount of carbon will be too expensive to implement.

4. AN ANALYTICAL INVESTIGATION OF MARKET DESIGN

A broad understanding of potential unintended consequences in net emissions response under the alternative carbon market forms and possible policy designs can be developed using an analytical model. Here we use a relatively simple analytical model to examine cases where reactions to a market may generate both greater net emissions than the without-market case and substantially less negative sequestration and offsets than under the mandatory case. We will also posit policy design procedures to avoid such difficulties; we will develop this in several stages.

4.1 Basic Analytical Model—No Carbon Market

Assume a producer maximizes profits when choosing between two technologies, the commonly used baseline approach, x_1, and a more costly net-emissions-reducing alternative, x_2. In the absence of a carbon market, we assume the producer solves the following optimization problem:

$$Max \quad \pi = (px_1 + px_2) - x_1C_1(x_1) - x_2C_2(x_2)$$

$$\text{s.t.} \quad x_1x_2 = 0$$

$$x_1, x_2 \geq 0$$

where x_1 is the baseline strategy used. By assumption, x_1 has lower cost but higher emissions than the new previously unused alternative, x_2. Both alternatives produce the same amount of output. Assume that p is the per-unit revenue from that output. Additionally, $C_i(x_i)$ is the cost function of producing x_i. The constraint implies that farmers adopt either x_1 or x_2 but not both of them.

In setting up the model, we will use a linear, increasing cost function for producing more of x_i.

$$C_i(x_i) = c_i + dx_i$$

$$c_2 > c_1$$

$$p - c_i > 0; \;\; d > 0$$

where c_i and d are positive constants, with the cost of x_2 exceeding that of x_1 due to c_2 being greater than c_1 and, for simplicity, the costs under the two alternatives both rising at the same rate (d) with activities.

If we optimize this with calculus, we arrive at the solution for the baseline that x_1 is produced and x_2 is not.

$${x_1}^* = \frac{p - c_1}{2d} \;\; and \;\; {x_2}^* = 0$$

In this case, when e_i denotes the net emissions from the use of x_i, the total net carbon emission, EB^*, in the absence of a carbon market is:

$$EB^* = \frac{e_1(p - c_1)}{2d}$$

This will be the baseline amount under the absence of carbon market and e_1 will be the per unit performance standard that the market must do better than under the voluntary market.

4.2 Adding a Mandatory Carbon Market

Now suppose we examine the consequences of adding a carbon market under a mandatory program (where all are assumed to participate). In that case, the model becomes the following:

$$\pi = (px_1 + px_2) - x_1C_1(x_1) - x_2C_2(x_2) - M(E - EB^*)$$

$$\text{s.t.} \quad E = x_1e_1 + \ x_2e_2$$

$$x_1x_2 = 0$$

$$x_1, x_2 \geq 0$$

where M is the carbon price, E is the total emissions under the coice of the x_i, and EB^* is the baseline emissions quantity, as previously defined.

Under this policy setting, the production strategy will change due to the carbon price when the revenue from carbon market sales compensates for the difference in cost between the new and baseline technologies. If not, they will continue using the baseline technology.

So we have $x_{1,m}^*$ being produced when the carbon price is low.

$$x_{1,m}^* = \frac{p - c_1 - Me_1}{2d} \ ; \ x_{2,m}^* = 0 \quad when \ \ M < \frac{c_2 - c_1}{e_1 - e_2}$$

And $x_{2,m}^*$ will be produced instead of $x_{1,m}^*$ when the carbon price increases above the critical value.

$$x_{2,m}^* = \frac{p - c_2 - Me_2}{2d} \ \ ; \ x_{1,m}^* = 0 \quad when \quad M > \frac{c_2 - c_1}{e_1 - e_2}$$

Here, we need to add an assumption that $d < \min(|Me_1|, |Me_2|, |M(e_2 - e_1)|)$. Otherwise the incentive from program can not compensate the increase in production cost which means the program will have no influence on farmers' decisions.

Farmers will reduce their production levels of x_1 when the carbon price M is positive and will receive a payment for that reductions while producing x_1 when the carbon payment is not large enough to cause the shift to x_2. x_2 will also decline as the carbon price increases above the critical level. Therefore, this program will achieve emissions reductions across the spectrum of carbon prices. The emissions level given the optimal choice of x_i is:

$$E_m^* = e_1 x_{1,m}^* + e_2 x_{2,m}^*$$

Also, the reductions level, $EB^* - E_m^*$, can be calculated by substituting E_m^* with the expressions from above, given $x_{1,m}^*$ and $x_{2,m}^*$. So we have the reduction level under low carbon price as:

$$EB^* - E_m^* = \frac{Me_1^2}{2d} \; ; \quad when \;\; M < \frac{c_2 - c_1}{e_1 - e_2}$$

And the reduction level under the high carbon price is:

$$EB^* - E_m^* = \frac{(p - c_1)(e_1 - e_2) + e_2(c_2 - c_1 + Me_2)}{2d} \; ; \quad when \;\; M > \frac{c_2 - c_1}{e_1 - e_2}$$

So compared with the no-carbon-market scenario, a net emissions reductions will occur with a mandatory program regardless of carbon price for positive emitting strategies because M, d and e_2 are positive. For strategies generating negative emission, we will discuss this issue later.

4.3 Voluntary Program

The prospect of implementing a mandatory carbon market has not been well received politically in the US, as evidenced by the cap-and-trade discussion (Lyon 2003). Thus, some have suggested that a voluntary market might be implemented. As discussed above, the form we study is that producers may be paid to join a market if they can reduce emissions relative to prior practices, and they will be paid according to the difference. Analytically, this leads to a model of the form:

$$Max \quad \pi = (px_1 + px_2) - x_1 C_1(x_1) - x_2 C_2(x_2) - M[(x_1(e_1 - e^b) + x_2(e_2 - e^b)\,]$$

$$\text{s.t.} \quad x_1 x_2 = 0$$

$$x_1, x_2 \geq 0$$

where e^b is the baseline emissions per unit of production that voluntary or opting-in producers must achieve if they wish to receive payment. In this case, producers only get paid if their net emissions level is less than the baseline emissions level, so we set $e^b = e_1$. In turn, continuing to use x_1 yields no carbon market payments, while using x_2 results in revenue from a payment equaling, $Mx_2(e_1 - e_2)$. Therefore, the optimal choices under low carbon price are:

$$x_{1,v}^* = \frac{p - c_1}{2d}\ ;\ x_{2,v}^* = 0 \quad when \quad M < \frac{c_2 - c_1}{e_1 - e_2}$$

And the production levels under high carbon price are:

$$x_{2,v}^{*} = \frac{p - c_2 - M(e_2 - e_1)}{2d} \ ; \ \ x_{1,v}^{*} = 0 \quad when \quad M > \frac{c_2 - c_1}{e_1 - e_2}$$

In this case, farmers voluntarily enter the program using x_2 , the new emissions-reducing technology, if M exceeds the above threshold.

So now let us look at how emissions levels are affected by payments under the voluntary program (note emissions are constant when producing x_1 and the net amount of payment is zero because this does not involve market participation). The resultant emissions above the threshold for x_2 are:

$$E_v^{*} = \frac{e_2[p - c_2 - M(e_2 - e_1)]}{2d}$$

where E_v^{*} is the emissions under participation in the voluntary program. We can see from the equation above that the emissions are positive correlated with carbon price for positive emitting strategies which means $e_2 > 0$ and negative correlated for strategies generating negative emissions.

Now suppose we examine the size of the net emissions relative to those in the no-carbon-market case. Here we will derive the difference and substitute c_2 with $c_1 + \Delta c$ and e_2 with $e_1 + \Delta e$.

$$E_v^{*} = \frac{(e_1 + \Delta e)[p - (c_1 + \Delta c) - M(\Delta e)]}{2d}$$

Further expand the formula and we get:

$$E_v^* = \frac{e_1[p-(c_1+\Delta c)-M(\Delta e)]}{2d} + \frac{\Delta e[p-(c_1+\Delta c)-M(\Delta e)]}{2d}$$

In order to compare E_v^* with EB^*, we divide the first term into two parts as follows:

$$E_v^* = \frac{e_1(p-c_1)}{2d} + \frac{e_1[-\Delta c - M(\Delta e)]}{2d} + \frac{\Delta e[p-(c_1+\Delta c)-M(\Delta e)]}{2d}$$

By subtracting EB^* from both sides, we can drive the reduction levels.

$$E_v^* - EB^* = \frac{e_1[-\Delta c - M(\Delta e)]}{2d} + \frac{\Delta e[p-(c_1+\Delta c)-M(\Delta e)]}{2d}$$

In order to analyze the program effect on positive emitting strategies, meaning $e_1 \; and \; e_2 > 0$, we need to dig deeper. Here we substitute e_1 with $e_2 - \Delta e$ in the equation above.

$$E_v^* - EB^* = \frac{(e_2-\Delta e)[-\Delta c - M(\Delta e)]}{2d} + \frac{\Delta e[p-(c_1+\Delta c)-M(\Delta e)]}{2d}$$

After simplify the equation we can get:

$$E_v^* - EB^* = \frac{-e_2\Delta c + \Delta e(p-c_1) - \Delta e M e_2}{2d}$$

Now we can solve the range of M by assuming the left hand side is positive.

$$E_v^* - EB^* > 0 \quad when \quad M > \frac{c_2-c_1}{e_1-e_2} + \frac{p-c_1}{e_2}$$

From this we can see that the voluntary program payment can have a counter effect causing a total emissions increase above the baseline level. The last equation indicates that when M is larger than the amount to stimulate production of x_2 by $\frac{p-c_1}{e_2}$, the extra emissions from producing x_2, which is $x_2 e_2$, will make the total emissions exceed the baseline level. This extra emission offsets the emissions savings from the difference between the two alternatives. And we can show this by first driving the derivative of M over E_v^* as:

$$\frac{\partial E_v^*}{\partial M} = \frac{e_2(e_1 - e_2)}{2d} \quad when \quad M > \frac{c_2 - c_1}{e_1 - e_2}$$

Here we can express the changes in emissions as a function of changes in carbon price.

$$\Delta E_v^* = \Delta M \frac{\partial E_v^*}{\partial M}$$

Now we know the condition of carbon price under which the additional emissions offset the mitigation effect from adopting x_2 strategy.

$$\Delta E_v^* > x_1^*(e_1 - e_2) \quad when \quad \Delta M > \frac{p - c_1}{e_2}$$

ΔE_v^* is the increment of emissions which equals the product of the increment of M and the derivative of M over E_v^* since the emission amount can be expressed as a linear function of M. Therefore we can derive the last equation above and see that the extra emission from production increase will offset the emission reductions achieved by switching production alternatives. So the voluntary program will cause the rebound effect if carbon price meets the condition above.

Additionally, suppose we compare the voluntary program with the mandatory program. We can derive the reductions level rather simply. Under the high carbon price situations the reduction level is:

$$E_v^* - E_m^* = \frac{Me_1e_2}{2d} \quad when \quad M > \frac{c_2 - c_1}{e_1 - e_2}$$

When the carbon price is lower than the critical value, the reduction level is:

$$E_v^* - E_m^* = \frac{Me_1^2}{2d} \quad when \quad M < \frac{c_2 - c_1}{e_1 - e_2}$$

It is highly unlikely that $e_1 > 0$ and $e_2 < 0$ for a crop, so $E_v^* - E_m^*$ is non negative at all carbon prices for all strategies. Therefore the voluntary program will certainly bring a lower level of emissions reductions than the mandatory program. The numerical exploration below will further illuminate this result.

4.4 Results for Strategies Generating Negative Emissions

When producing emission reducing substitute products or enhancing sequestration, there will be baseline and alternative strategies that generate negative emissions. This merits examination in terms of whether or not the voluntary program affects the potential adoption of such technologies and the amount of negative offset achievable.

Based on the previous analysis, we know that the emission difference between the mandatory program setup and the no carbon market scenario can be expressed as follows for low carbon price.

$$EB^* - E_m^* = \frac{Me_1^2}{2d} \ ; \quad when \ \ M < \frac{c_2 - c_1}{e_1 - e_2}$$

And for a high carbon price, the difference is:

$$EB^* - E_m^* = \frac{(p - c_1)(e_1 - e_2)}{2d} + \frac{e_2(c_2 - c_1 + Me_2)}{2d} \ ; \quad when \ \ M > \frac{c_2 - c_1}{e_1 - e_2}$$

It is easy to see from the first equation that the mandatory program will achieve emission reductions when carbon price is below the critical value. For strategies generating negative emissions, we can further examine the second equation and draw conclusions.

Since $M > \frac{c_2 - c_1}{e_1 - e_2}$ and $e_2 < 0$, we can multiply e_2 on both sides of the condition over M and get:

$$Me_2 < \frac{c_2 e_2 - c_1 e_2}{e_1 - e_2}$$

which is the revenue to program participation. If we add in the cost difference, the net revenue implications are:

$$c_2 - c_1 + Me_2 < \frac{e_1(c_2 - c_1)}{e_1 - e_2}$$

Because of $e_1 > e_2$, $c_2 > c_1$ and $e_1 < 0$, and we know that the right hand side of the equation above is negative. Therefore the left hand side must also be negative and if we multiply it by $\frac{e_2}{2d}$ we can see that:

$$\frac{e_2(c_2 - c_1 + Me_2)}{2d} > 0$$

This term above is a part of emissions reductions under mandatory program and it is increasing as M grows.

$$EB^* - E_m^* = \frac{(p - c_1)(e_1 - e_2)}{2d} + \frac{e_2(c_2 - c_1 + Me_2)}{2d} \; ; \quad when \;\; M > \frac{c_2 - c_1}{e_1 - e_2}$$

Since $\frac{(p-c_1)(e_1-e_2)}{2d} > 0$, now we can draw the conclusion that $EB^* - E_m^* > 0$ for strategies generating negative emission at all carbon prices. The mandatory program will encourage the production of emission reducing substitute products and will enhance the adoption of the negative emissions strategies. Also the mandatory program will reduce more and more emissions as the carbon price keep increases.

For strategies generating negative emissions, the implementation of the voluntary program will also lead to emission reductions. Based on the previous analysis on the voluntary program we know that:

$$E_v^* - EB^* = \frac{e_1[-\Delta c - M(\Delta e)]}{2d} + \frac{\Delta e[p - (c_1 + \Delta c) - M(\Delta e)]}{2d}$$

We can apply $x_{2,v}^* = \frac{p - c_2 - M(e_2 - e_1)}{2d}$ here and get the following:

$$E_v^* - EB^* = \frac{e_1[-\Delta c - M(\Delta e)]}{2d} + x_{2,v}^*(\Delta e)$$

Here Δe is negative so the second term on the right-hand side is negative. We also know that participation in the program requires the condition $M > \frac{\Delta c}{-\Delta e}$. So if $e_1 < 0$

which is the case for a negative emitting strategy, the voluntary program will reduce total emissions compared with the no carbon market scenario when carbon price is above the critical value. When the carbon price is not high enough and farmers choose not to participate in the program, no payment will be made and the emissions will remain unchanged under the voluntary program.

To compare the voluntary program and mandatory program for negative emitting strategies, we can use the equations we derived before for the difference in emissions between the voluntary (E_v^*) and mandatory (E_m^*) programs. The differences in emissions under the high carbon price are:

$$E_v^* - E_m^* = \frac{Me_1e_2}{2d} \quad when \quad M > \frac{c_2 - c_1}{e_1 - e_2}$$

When the carbon price is low, the differences are:

$$E_v^* - E_m^* = \frac{Me_1^2}{2d} \quad when \quad M < \frac{c_2 - c_1}{e_1 - e_2}$$

It is clear that the total emission reducing effects of the mandatory program is larger (in a negative sense) than that of the voluntary program $E_v^* - E_m^* \geq 0$ at all carbon prices. Also note that the emissions difference is a linear function of M which means as the carbon price increases that the gap between two programs expands proportionally. Therefore when the carbon price is large, especially above the critical value, this gap can be large which means that the voluntary program can bring far less emission reductions.

We can also see how the voluntary program under these assumptions dampens participation by examining the effects on the level of x_2 under the two programs.

Under the mandatory program the production of x_2 equals to the following:

$$x^*_{2,m} = \frac{p - c_2 - Me_2}{2d} \quad when \quad M > \frac{c_2 - c_1}{e_1 - e_2}$$

While under the voluntary program it equals to:

$$x^*_{2,v} = \frac{p - c_2 - M(e_2 - e_1)}{2d} \quad when \quad M > \frac{c_2 - c_1}{e_1 - e_2}$$

And the differences are:

$$x^*_{2,m} - x^*_{2,v} = \frac{-Me_1}{2d}$$

Here note since e_1 is negative and M and d are positive, the voluntary program stimulates less production of x_2 than does the voluntary program. Notice here, the gap between productions of x_2 is also a function of M so the gap rises as the carbon price rises.

We can also conclude that while the voluntary program reduces net total emissions compared to the no carbon market case it does not do this as much as the mandatory program.

4.4.1 A payment design for negative emitting strategies

Another issue we need to discuss is payment design. For people who create negative emissions, payments based on emissions status improvement, which is $e_1 - e_2$, may not be enough to lead to a production increase (where x_2 is substantially greater than the without market optimal x_1^*). Here we may want to design the program to enlarge the support for negative emitting strategies that are implemented above the baseline levels resulting in a greater effect on the amount of net emissions reductions. In order to avoid making too many changes for the model, we add a variable for the amount of x_2 beyond the baseline amount of x_1 and call this x_3 in turn setting the model as follows for the negative emitting voluntary case:

$$\pi = p(x_1 + x_2 + x_3) - x_1 C_1(x_1) - (x_2 + x_3) C_2(x_2 + x_3) - M(x_2(e_2 - e_1\ ) + x_3 e_2)$$

$$\text{s.t.} \quad x_1 + x_2 \geq x_1^*$$

Here, both x_2 and x_3 are mitigation practices that have less emissions and higher cost. x_1^* is the production level achieved without any program payment. And x_3 represents production from the land that is not used for x_1 or x_2 initially. This is equivalent to setting eb, the per unit offset, to zero for additional negative emitter production beyond the baseline level. In other words, if farmers decide to further expand their production well beyond the levels they produced in the baseline for negative emitting strategies, they will receive payment based on the additional amount of emissions offset for production beyond the baseline amount. The constraint we added here makes sure that only the additional production will receive full payment and that farmers will only be paid for the offset improvement they generate for the production amount that was in the original baseline. Namely, each unit of x_2 is paid $M(e_2 - e_1)$, but this payment rate only covers up to the baseline amount, x_1^*. For production in addition to x_1^*, which is x_3, the payment rate is Me_2. The reason we split the mitigation practice into two parts is that we can easily implement constraints to prevent the production dampening amount that stops expansion beyond the x_1^* amount.

Under this payment setting, the negative emitters receive bigger incentives for additional production that is larger than the no-program amount. Since x_2 is less attractive than x_3 in the objective function and we have a minimum requirement for it, x_2 will remain constant at its lower bound of x_1^* when the mitigation practice is adopted. Also the per-unit emission is negative, so we do not need to worry about the expansion of total emissions. As always, the optimal solution for x_2 and x_3 in this setting changes based on the carbon price. When the carbon price is below the critical value:

$$x_{1,s}^* = x_1^* \,; \quad x_{2,s}^* = 0\,; \quad x_{3,s}^* = 0 \;\; when \;\; M < A$$

When the carbon price is above the critical value:

$$x_{1,s}^* = 0\,; \quad x_{2,s}^* = x_1^*\,; \quad x_{3,s}^* = \frac{c_1 - c_2 - Me_2}{2d} \quad when \;\; M > A$$

where A is the critical value of carbon price above which the mitigation practices will be adopted. The critical value here is smaller than what we have seen before because the payment for additional negative offsets is larger for x_2 and x_3. The closed-form expression for A is intricate, so we just qualitatively discuss it here. A numerical example will be demonstrated later where the value of A is calculated.

Here the emission levels are:

$$E_{v,s}^* = \frac{e_2(p - c_2 - Me_2)}{2d} \quad when \quad M > A$$

4.4.2 A special case where there is no new technology

A special case may be considered where the participating technology is basically the same as that in the baseline and thus e_2 is about the same as e_1. This strategies case creates a substantial difference if we don't have the design above that involves x_3. In particular there is very little space for the negative strategies producers to further enhance their performance but if they would expand production substantially then net emissions would fall.

Here we examine the case where the emissions under the technologies are essentially the same.

$$e_1 - e_2 \to 0$$

Under this case the critical value of carbon price will be very large and will lead to no voluntary participation and no gain in total net emissions reduction. In particular the critical price is:

$$\frac{c_2 - c_1}{e_1 - e_2} \to \infty$$

In that case the alternative practice will likely never be adopted which means only x_1 is produced and emissions reduction is zero. Even when the carbon price rises above the critical value, here we only get the emissions reductions as follows:

$$E_v^* - EB^* \to \frac{e_2(c_1 - c_2)}{2d} \quad when \quad M > \frac{c_2 - c_1}{e_1 - e_2}$$

However under the voluntary program with special payment design, we can achieve emissions reductions at the same price range as follows:

$$E_{v,s}^{*} - EB^{*} = \frac{(p - c_1)(e_2 - e_1) - Me_2^2 + e_2(c_1 - c_2)}{2d}$$

Apply the assumption made above and we can further get:

$$E_{v,s}^{*} - EB^{*} \rightarrow \frac{e_2(c_1 - c_2) - Me_2^2}{2d}$$

The formula above shows that the emission reductions under the special payment design is a linear function of carbon price. So as M increases the emission reductions rise as well. Meanwhile we need to notice the fact that the original voluntary program which pays for the emissions improvement achieves almost zero emission reduction under the same assumption.

The reason for this difference is the emission brought by x_3 which equals to:

$$x_{3,s}^{*} e_2 = \frac{e_2(c_1 - c_2 - Me_2)}{2d}$$

This term is negative and its absolute value increases as M increases which means more emission reductions can be achieved as carbon price rises. Since x_3 was defined as the production from land that was not used for x_1 or x_2, the voluntary program with special payment design is able to bring new land into production of negative emitting strategies. For reforestation and biofuel production there is typically not much of an option available to further improve the mitigation performance on the land that are already covered by forest or used for biomass production and the baseline levels of these activities may be quite small. Therefore emission improvement potential is small and as we showed before the original voluntary program cannot cause much changes. On the other hand, the special payment design can convert additional land into forest or encourage farmers to produce additional biomass. We will revisit this significant effect on the negative emitting strategies in the empirical model later.

4.5 Program Constraints

It is possible that program designs can be altered to avoid the unintended consequences of emissions increases and lower levels of negative offset potential. In particular, for an emitter, one needs to limit the eligible amount of the improved practice to its baseline amount. For a producer of negative emissions, one needs to enhance the production eligible for payment. To achieve these goals, we can implement production constraints or carbon price constraints.

4.5.1 Price constraint

For the price constraint, we already know that total emissions will increase if:

$$M > \frac{p - c_1}{e_2} + \frac{c_2 - c_1}{e_1 - e_2}$$

So we can add to the model that:

$$M < \frac{p - c_1}{e_2} + \frac{c_2 - c_1}{e_1 - e_2}$$

It is theoretically acceptable, and we need to estimate the fixed cost under each technology that might be costly or infeasible in practice. The shadow price on this constraint, if is not zero, measures the changes in farmer income if the carbon price changes by one unit.

4.5.2 Production constraint

Adding a constraint on production level is much easier. We can impose a constraint in the program as follows:

$$x_2 \leq \frac{p - c_1}{2d}$$

Here we do not allow the production level to expand beyond the baseline level that it should achieve without program support. Therefore, the program will not pay for extra production level and total emissions will not increase. The only issue is that this constraint will impede the production of negative emitting strategies. So we need further add that:

$$x_2 \leq \frac{p - c_1}{2d} \quad for \quad e_2 > 0$$

It is also possible to add constraints that take care of negative emitters in the program. We can impose a constraint to prevent production from decreasing. If strategy x_1 will be adopted, we can impose a minimum requirement equals to its baseline production amount.

$$x_1 \geq \frac{p - c_1}{2d} \quad for \quad M < \frac{c_1 - c_2}{e_2 - e_1} \quad and \quad e_2 < 0$$

If strategy x_2 is chose, we can also add a lower bound as follows:

$$x_2 \geq \frac{p - c_2}{2d} \quad for \quad M > \frac{c_1 - c_2}{e_2 - e_1} \quad and \quad e_2 < 0$$

The combination of production constraints and special payment for negative emitting strategies involves a slight change in the model structure. We can adjust the model as follows for the voluntary program:

$$\pi = p(x_1 + x_2 + x_3) - x_1 C_1(x_1) - (x_2 + x_3) C_2(x_2 + x_3) - M(x_2(e_2 - e_1) + x_3 e_2)$$

$$\text{s.t.} \quad x_2 \leq \frac{p - c_1}{2d}$$

$$x_1 + x_2 \geq \frac{p - c_1}{2d}$$

$$x_1 x_2 = 0$$

$$x_1, x_2, x_3 \geq 0$$

As we discussed in the special payment section, x_2 and x_3 are production under mitigation practices. The first constraint limits production of x_2, so a rebound effect will not take place if the strategies have positive emissions. The second constraint provides a minimum production requirement that equals the baseline amount and will force the non-additional activity to be as big as the baseline amount. The third and fourth constraints rule out the possibility that both alternatives are adopted. Together, the first three constraints make sure that at least one of x_1 and x_2 will be produced at the baseline amount. For the positive emitters, x_3 will be zero because it has a negative coefficient in the objective function. For strategies with negative emissions, if the mitigation practices are adopted, producing x_3 will receive larger incentives and there is no limit on the production level.

This modification encourages farmers to expand their production on strategies with negative emissions and causes the production of positive emitting strategies to only get incentives if the production is at or below the baseline amount, regardless which technology they choose precluding the unintended consequences.

4.6 A Multi-Strategies Model

It is possible to derive a multi-strategies model for the program, but it requires additional constraints to draw conclusions. So it is not helpful to set up an objective function for the general case. However, discussion of a special case will benefit our understanding of the potential effects of the program.

The issue we wish to clarify here is the possible shift from energy strategies to positive emitting strategies under an incentive from the program after previous changes. In other words, farmers who should have planted energy strategies will choose to cultivate positive emitting strategies, like rice, in order to receive payment from the program. It is possible that total emissions will increase dramatically. Here we set up an objective function:

$$\pi = p_A(x_1 + x_2) - x_1C_1(x_1) - x_2C_2(x_2) - M[x_1(e_1 - e_2)\ ]^{opt}$$

$$+p_B(x_3 + x_4) - x_3C_3(x_3) - x_4C_4(x_4) - (ME_B)\ ^{opt}$$

Crop B is an energy crop, and crop A is emitting crop. p_A and p_B are the prices of two strategies. x_3 and x_4 are productions of crop B under traditional and emission-mitigated technologies, respectively. E_B is the total emissions from crop B, and opt is a binary variable that only takes the value of one or zero, providing an easy way to set up the voluntary program. Here we have the same assumption for both strategies as we did before. Therefore, we add together the income from two strategies to analyze this issue.

Based on the background information, it is reasonable to assume that emitting strategies are more profitable than energy strategies, and the emissions improvement for crop A is less than the total emissions amount for crop B. So we have the following conditions:

$$p_A - c_1 < p_B - c_4$$

$$e_2 - e_1 > e_3$$

$$e_1, e_2 > 0 \quad and \quad e_3, e_4 < 0$$

To avoid unnecessary work, we can further assume that $c_1 - c_2 = c_3 - c_4$, which means switching between technologies cost the same for both strategies. So we can derive that

$$\frac{c_1 - c_2}{e_2 - e_1} < \frac{c_3 - c_4}{e_4 - e_3}$$

The two quantities above are the two critical values for carbon price. If carbon price is less than $\frac{c_1 - c_2}{e_2 - e_1}$, farmers will choose the traditional technology for both strategies. If carbon price is larger than $\frac{c_3 - c_4}{e_4 - e_3}$, farmers will adopt advanced technology. Since the advanced technology has a higher cost, we can conclude that if there exists a carbon price that makes crop A more profitable than crop B, it must lie between these two critical values. We are finding a carbon price that makes planting crop A with advanced technology worth more than planting crop B traditionally. Therefore, the carbon price will have the following boundaries:

$$\frac{(p_B - c_4) - (p_A - c_1)}{e_4 - (e_1 - e_2)} < M < \frac{c_3 - c_4}{e_4 - e_3}$$

We can denote $p_A - c_1$ as MR_{A1}, the marginal revenue of crop A using advanced technology, and $e_1 - e_2$ as I_A, the carbon emissions improvement of crop A. Then the conditions can be rewritten:

$$\frac{MR_{B4} - MR_{A1}}{e_4 - I_A} < M < \frac{c_3 - c_4}{e_4 - e_3}$$

So if the carbon price can compensate the difference between the marginal revenue of two strategies, farmers will choose positive emitting strategies with advanced technology rather than bioenergy. To avoid this unpleasant result, we need to set boundaries for carbon price.

5. EMPIRICAL MODEL

In this section, we are going to demonstrate our results from the previous section using an empirical mathematical programming model. We will set up this model with parameter values that are specified based on a case of emissions reductions in rice production for the emitter situations and the use of switchgrass for electricity generation for the negative emitter. Relevant data are collected from the Economic Research Service (ERS) Website and the studies mentioned below.

5.1 Modeling Framework

The objective function is as follows, covering all the possible formulas presented before:

$$\begin{aligned}\text{Max}\quad & p(x_1+x_2+x_3)-x_1C_1(x_1)-(x_2+x_3)C_2(x_2+x_3)\\ & -M[x_1(e_1-e_b)+x_2(e_2-e_b)-baseline-e_2x_3]\\ \text{s.t.}\quad & x_1x_2=0\\ & x_1+x_2\geq x_1^*\\ & x_1,x_2,x_3\geq 0\end{aligned}$$

We can derive different results by changing the value of parameters in this function. For the no carbon market scenario, we set $M=0$. When analyzing the mandatory program, we use the conditions $e_b=0$, $x_3=0$ and $baseline=x_1^*e_1$, where x_1^* is the optimal we solved for when $M=0$. For the voluntary program, we can change the setting into $e_b=e_1$, $baseline=0$ and $x_3=0$. The special payment for negative emitting strategies can be achieved by letting $e_b=e_1$ and $baseline=0$.

As for the constraint $x_1x_2 = 0$, it is more convenient for solving if we set up the constraint as follows:

$$x_i - Az_i \leq 0$$

$$\sum_i z_i \leq 1 \quad i = 1,2$$

Here, A is a positive constant and z_i is a binary variable that only takes the value zero or one. The first equation makes sure that if x_i takes a positive value, z_i has to be one. The second equation shows that z_1 and z_2 cannot both be one which means that between x_1 and x_2 only one of them can be positive and the other one has to be zero.

5.2 Model Setup

As mentioned in the Commodity Costs and Returns data (USDA 2015), the average rice yield in the U.S. was 83 cwt per acre, with the price around $15.5 per cwt. From USDA (2015), we also know that the operating cost for rice is around $602 per acre and the allocated overhead cost including hired labor is about $413 per acre. Mid-season drainage is a common mitigation practice for rice production. Pathak et al. (2012) showed that this practice will reduce emissions from 3 tons of CO_2 equivalent per hectare to 2 tons of CO_2 equivalent per hectare based on global warming potential. This practice also requires additional hired labor and extra commercial drying expenditure. Therefore, we can calculate all the parameters needed in the model on a per-ton basis.

For the negative offsets case, we calculated the parameters based on switchgrass production. Duffy (2007) estimated the cost for switchgrass production, transportation, and storage in Iowa. Qin et al. (2006) used lifecycle analysis to estimate GHG emissions mitigation from switchgrass based on different co-firing ratios. For the price of switchgrass, since the market is not yet well established, we used the price of hay as a substitute. Hay prices vary largely based on their quality and production area; here we use average auction prices in Iowa in 2008 for a better match with the cost data. The negative emitting case here is just a demonstration for the analytical part. Further data are needed for a more practical analysis. The following table shows all the parameters used in the model on a per-ton basis.

Table 5.1 Value of parameters in empirical model.

	p ($/ton)	c_1 ($/ton)	c_2 ($/ton)	d ($/ton)	e_1 (tCO_2e/ton)	e_2 (tCO_2e/ton)
Positive emitter	276.78	218.57	224.18	1.25	0.2607	0.1732
Negative emitter	160	113	117	1.5	-1.42	-1.47

5.3 Model Results

We run this model multiple times under different carbon prices ranging from zero to over 400. Then we can show the production practice shift and production level changes as carbon price increases; the results are listed below.

5.3.1 Mandatory program

For the positive emitting strategies, the farmer will choose to adopt the mitigation practice only when the carbon price is high enough. As the charts below show, Figure 5.1 marks the level of x_1 or x_2 for the crop produced by the farmer, and Figure 5.2 gives tons of CO_2 equivalent emitted and the emissions under the baseline scenario, in which no carbon market exists. The horizontal axis is carbon price starting from zero. The critical value of carbon price is around $64.1 in this case. The production level is negatively correlated with carbon price. Therefore, the mandatory program will reduce carbon emissions at any price level, and the reductions are greatly increased beyond the critical price.

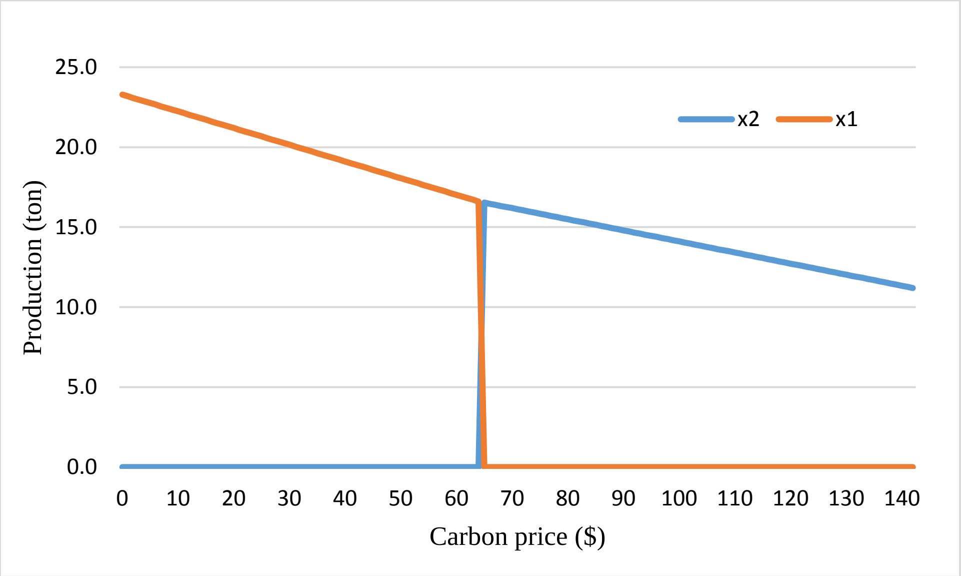

Figure 5.1 Production of positive emitting strategies under mandatory program

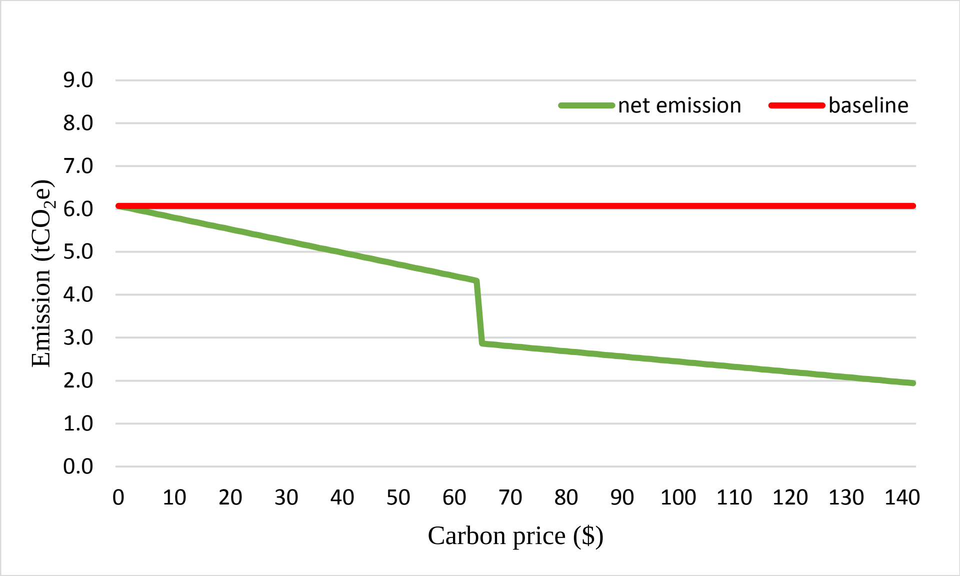

Figure 5.2 Emission of positive emitting strategies under mandatory program

Results for the negative emitter are shown in Figure 5.3 and Figure 5.4. The emissions reductions are not significant beyond the critical price, and the rest of the results are nearly the same. In the analytical part, we concluded that production level will decrease no matter what carbon price is, and total emissions will reduce in the mandatory program. Here our model results proved this conclusion.

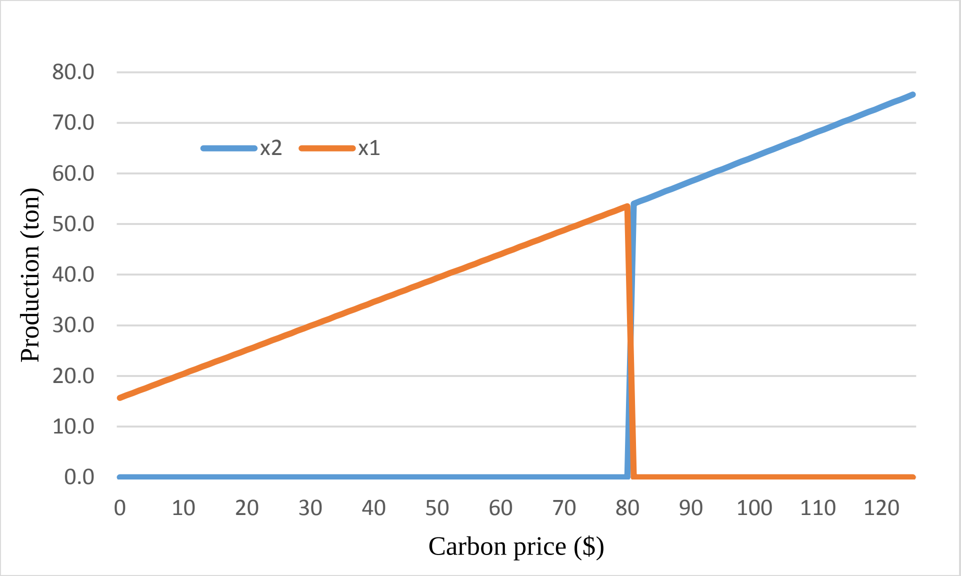

Figure 5.3 Production of negative emitting strategies under mandatory program

Figure 5.4 Emission of negative emitting strategies under mandatory program

5.3.2 *Voluntary program*

In the voluntary program, the minimum payment farmers can receive is zero when they do not participate. So GHG emissions will remain unchanged if the carbon price is not high enough for farmers to adopt the mitigation alternatives. But beyond that point, the production level is positively correlated with carbon price, making the rebound effect possible. In this case, the rebound effect takes place as the payment gets larger than the amount that induced production of x_1. In particular, as the payment rises, x_2 gets larger, and while the emissions per acre are reduced relative to the baseline, the total emissions start to rise, erasing some of the anticipated gain. Then when the carbon price reaches $400, total emissions actually exceed those in the baseline. Again this result is consistent with what we have shown before.

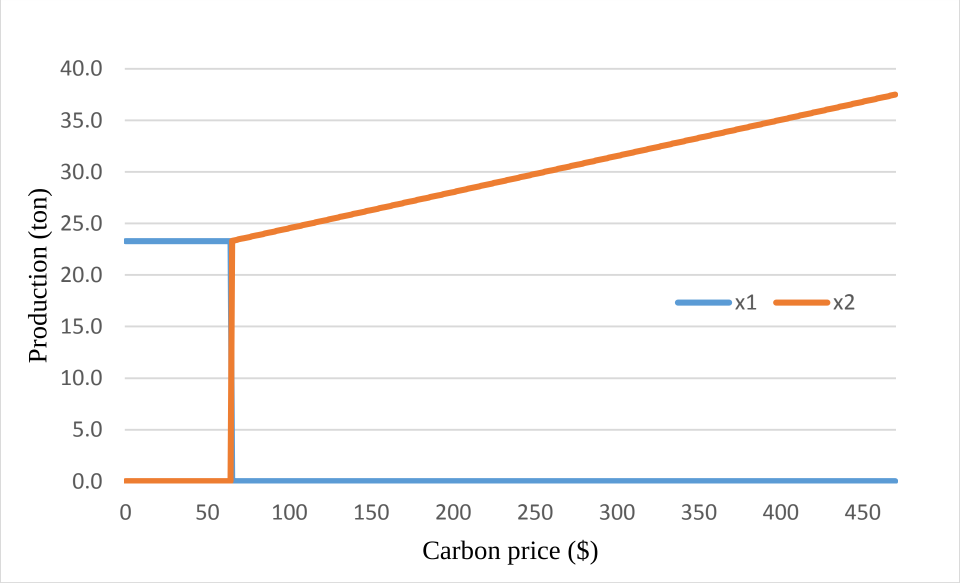

Figure 5.5 Production of positive emitting strategies under voluntary program

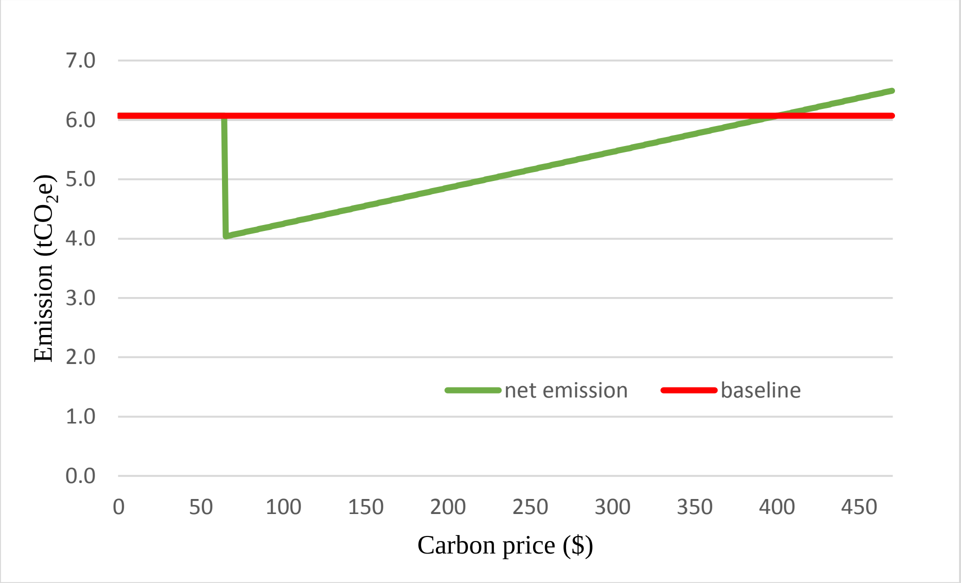

Figure 5.6 Emission of positive emitting strategies under voluntary program

In Figure 5.5, when farmers choose to produce x_2, the production of x_2 equals that of x_1 in the baseline. It is easy to see in Figure 5.6 that the largest reduction occurs right after the strategy shift. Additional carbon price will only lead to production expansion and greater total emissions. When the carbon price is above $400, the total emissions from the practice exceed the baseline amount in Figure 5.6

For the negative emitter, the voluntary program limits practice adoption. So the production level only increases a little. In Figure 5.7, we rescale the vertical axis in order to show the changes since they are smaller in range. Therefore, it is not shown in Figure 5.7 that production level is zero for x_1 and x_2.

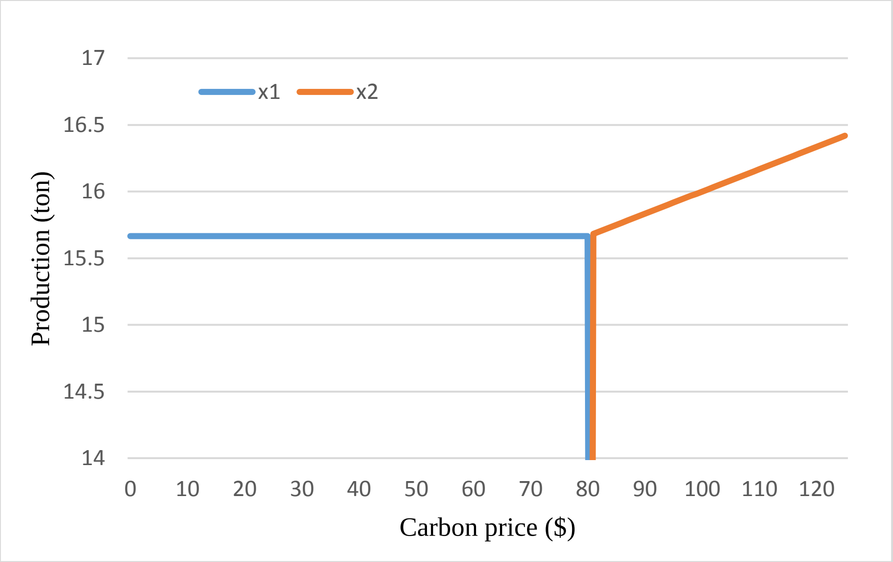

Figure 5.7 Production of negative emitting strategies under voluntary program

The emissions reduction is also not significant, as we can see from Figure 5.8.

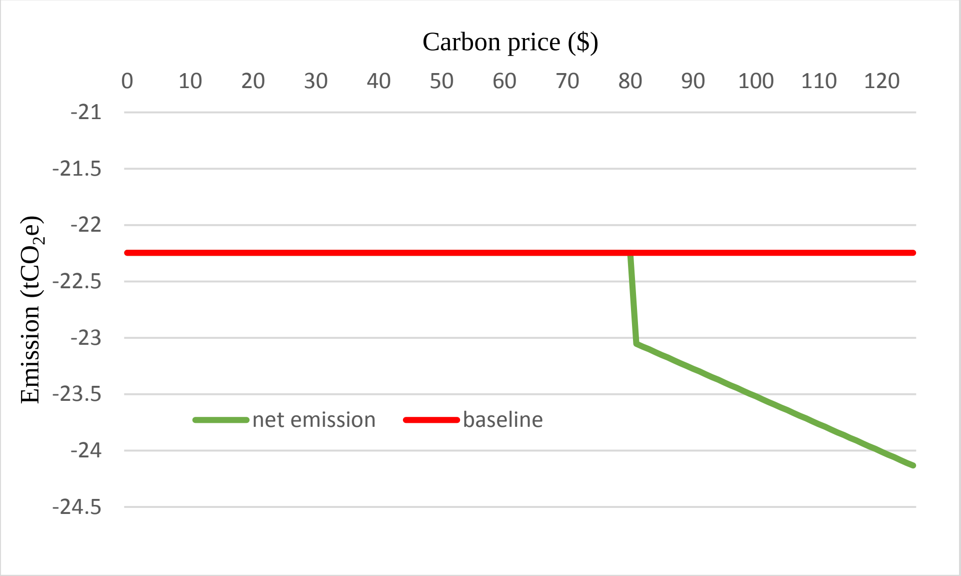

Figure 5.8 Emission of negative emitting strategies under voluntary program

5.3.3 *Special payment for negative emitter*

As we discussed before, as well as is shown by the model results, the voluntary program does not provide enough support for negative emitting strategies. So we need to design a special payment that pays for the total emissions amount instead of emissions status improvement when the participating land exceeds that in the baseline. We run the model again under the formula presented in the analytical section; the results are shown below. Both production level and emissions reductions increase dramatically within the same price range, and x_3 is brought into the optimal solution when carbon price is high enough to adopt the mitigation practice. Therefore, the special payment is effective to encourage GHG mitigation practices.

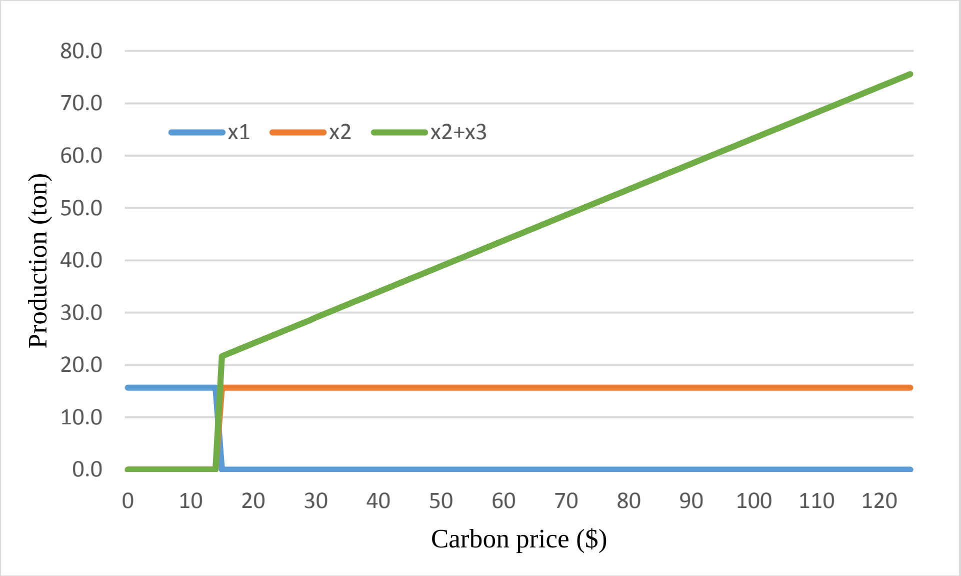

Figure 5.9 Production of negative emitting strategies under voluntary program with special payment design

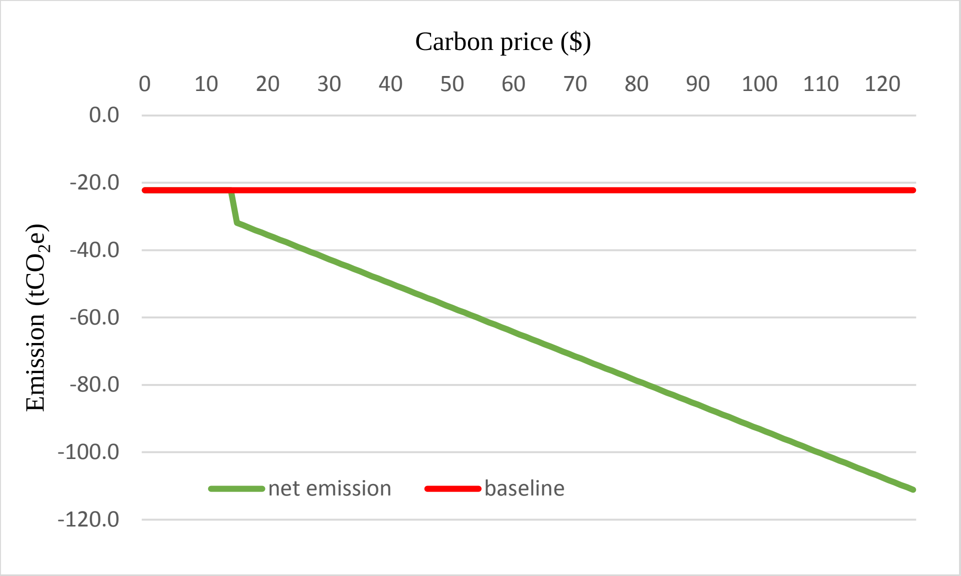

Figure 5.10 Emission of negative emitting strategies under voluntary program with special payment design

As showed in Figure 5.9, under this payment setting, farmers will adopt mitigation practices at a very small carbon price. In this case the critical value is

$$M = 14.64$$

In Figure 5.9 and Figure 5.10 the production level and emissions reductions greatly increase compared with the voluntary payment design without this incentive for additional production. This result proves that the special payment is helpful to encourage the production of negative emitter.

5.3.4 Comparison between programs

Now we can compare mandatory and voluntary programs based on their emissions reductions performance.

First we will look at the program effect on emitters. From Figure 5.11, we can see that the mandatory program surely has a larger emissions reduction at all carbon prices for positive emitters, and it does not show a rebound effect after the critical price. We also see emissions reductions for low carbon prices. Meanwhile in the voluntary program, the reduction amount reaches its maximum level at the critical price, which provides us an insight on desired carbon price design for the program.

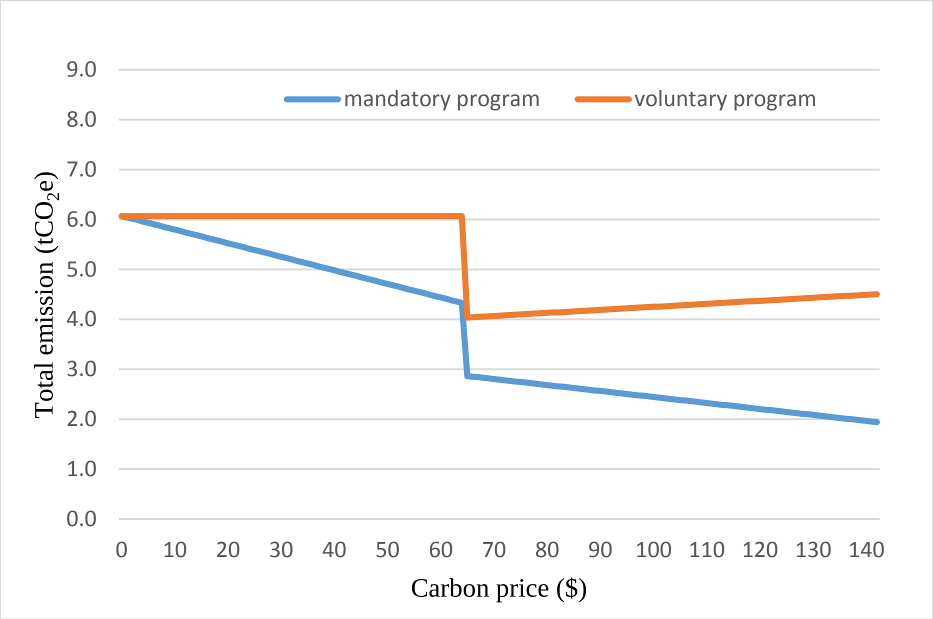

Figure 5.11 Comparison of emission for positive emitting strategies

The emissions reduction in the mandatory program comes from substantial production decrease, which is demonstrated in Figure 5.11. In Figure 5.12, we combine production levels, adding together x_1 and x_2 within the same program, as our focus here is the overall production level instead of practice chosen. Therefore the advantage of the mandatory program might be overestimated if we take into consideration a certain minimum production requirement. In addition, the mandatory program payment equals the product of reduction amount and carbon price, which also escalates as carbon price increases.

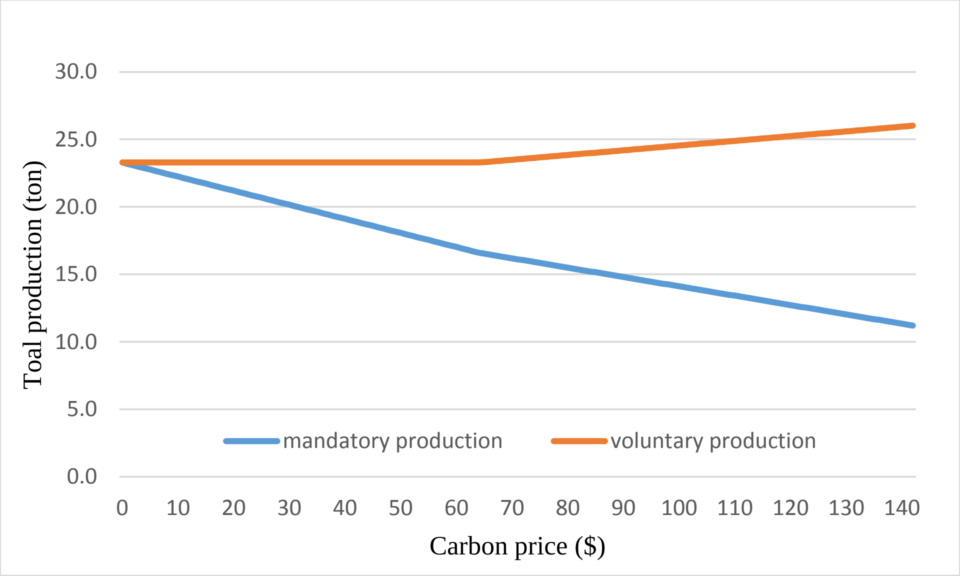

Figure 5.12 Comparison of production for positive emitting strategies

For the negative emitter, we provide Figure 5.13 and Figure 5.14 at different carbon price ranges for a better illustration. At low carbon prices, we can see in Figure 5.13 that the mandatory program induces the biggest negative emissions, and the original voluntary program has no effect. Emissions under the voluntary program with a special payment scenario exhibit gains almost as large as those under the mandatory program. Under higher carbon prices showed in Figure 5.14, after mandatory and voluntary programs reach their critical price, which is around $80, they all achieve an improvement in emissions offset amount. And the mandatory program has the same emissions amount as the voluntary program with special payment.

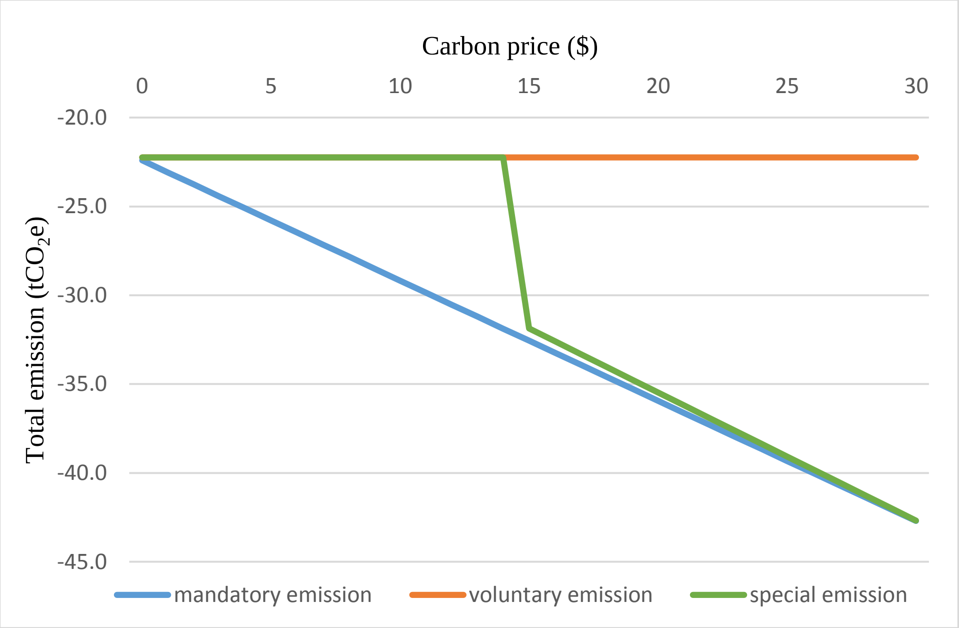

Figure 5.13 Comparison of emission for negative emitting strategies at lower carbon price levels

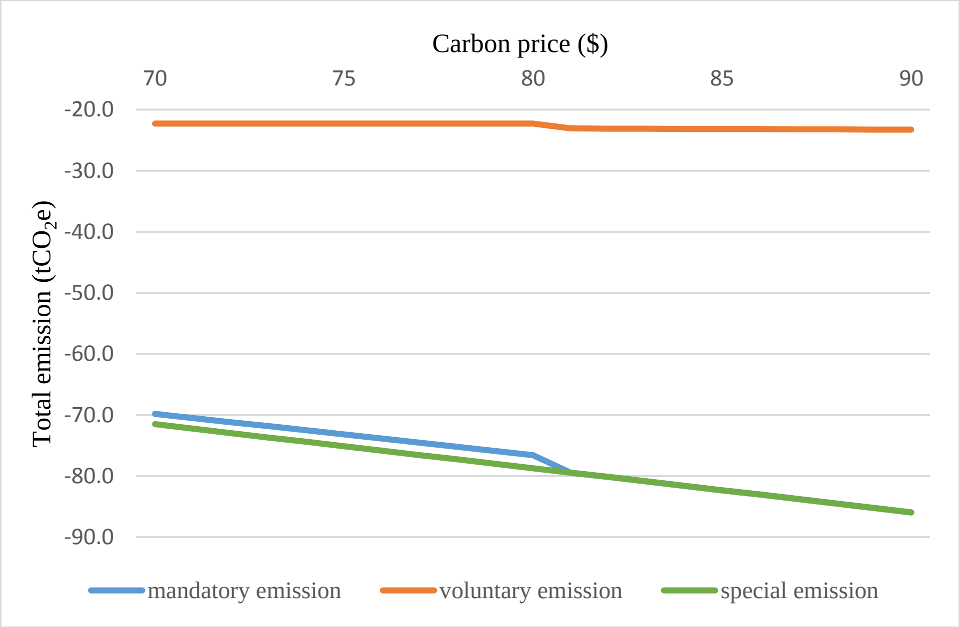

Figure 5.14 Comparison of emission for negative emitting strategies at higher carbon price levels

This result proves that the special payment design for negative emitting strategies will bring significant emissions reductions under a voluntary program format.

5.3.5 Adding constraints

Two types of constraints have been discussed to prevent the rebound effect and increase the additional amount for negative emitters. Here we will examine the outcomes of these constraints.

In order to avoid the rebound effect, we can limit carbon price within a range so that farmers cannot receive incentives for their additional production, or we can restrict the production directly. Certain forms of constraint have been designed in the analytical part and in Figure 5.15 are the results.

Figure 5.15 Comparison of emission for positive emitting strategies under two types of constraints

Before the critical value of carbon price, all three scenarios have the same emissions amount, which is the baseline amount because x_1 is the driver in this price range. After that, the production constraint has the best mitigation performance. The price constraint limits emissions amount below the baseline level. But the emissions reduction decreases when carbon price continues to increase. The power of the price constraint only reveals itself when carbon price is high enough to trigger the rebound effect. Because carbon price is unlikely to reach $400 per ton in reality, the production constraint might be a necessary part of the voluntary program.

For the negative emitters, we need to examine the effect of constraints on encouraging production expansion. The production constraint does not provide any limit or incentive for strategies with negative emissions, which makes it neutral in the voluntary program. On the other hand, the price constraint dampens the effect of the program because it stops carbon price from increasing.

From these results, we can draw the conclusion that price constraint is less beneficial than production constraint for its limited power on preventing rebound effect and its negative influence on encouraging production of negative emitters.

6. CONCLUSIONS

Agricultural mitigation practices may be a tool for use in achieving U.S. GHG net emissions reductions. But the agricultural sector has not yet been covered in currently existing carbon programs. Emissions reductions from agriculture have not been widely eligible for trading in carbon markets. Voluntary contracts between private parties and government are common in the agricultural sector; however, voluntarily involved programs may either cause total emissions to increase through a rebound or leakage effect or can reduce incentives to expand negative emissions, decreasing the potential magnitude of the offset.

In this study, we reviewed the issues of GHG emissions and potential carbon market designs. We also analyzed the underlying mechanisms of this program and derived conditions under which the rebound and negative emissions dampening effects will take place. Further, we came up with constraints that prevent this effect and program design elements that overcome these difficulties. Namely, we limit the voluntary participation of emitters to the level they experienced in the baseline and insure for negative emitters that the volume subject to the regional offset plus non-participants equals the activity in the baseline. We also make it possible to encourage negative strategies production to the baseline amount for those not currently enrolled to receive the full benefit if they decide to participate.

The empirical model results reinforce our analytical findings and show that production constraints are much more effective than price constraints. Therefore, a production constraint on positive emitting strategies, like rice, might be a necessary part of the program. And the special payment design for negative emitting strategies should also be taken into consideration for its significant effect on encouraging mitigation practices.

To apply the production constraint in the program design, one possible way is to limit the land or production enrollment to the levels in the baseline where no incentives are provided. The rebound effect will not take place because the additional production cannot receive payment from the program and the unintended consequence will be blocked. To apply the special payment design for negative emitting strategies, one needs to pay for the emissions improvement amount up to the baseline production level and the full offset amount for production beyond the baseline preventing the unintended dampening effect in that case.

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