The Influence of Credit Stacking Programs: The Coexistence of Regional Credits and Global Credits in Ecosystem Markets

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Abstract

In ecosystem service market, credit *stacking* generally refer to situation where the providers of ecosystem service credits are allowed to sell different types of credits in separate markets for each type, even as these credits might derive from a single entrepreneurial action, likely on a single parcel of land. With credit stacking permitted, credit production may overlap spatially for different services. Credit stacking policy may potentially bring more profits to market participants by allowing credit producer to sell all credits stacking on spatially overlapped area; while not allowing credit stacking may enable us to benefit from the "by product" for free due to production complementarity. In this research, we explore the implications when the regional credit, such water quality credit, is traded under the cap-and-trade framework while the price for the global credit, such as the carbon sequestration credit, is exogenous. We use the water quality credit and carbon sequestration credit as an illustrative example, realizing when a global market exists for the carbon credit, a single farmer has no influence in the market price. We find there exists a certain price threshold for the carbon price, under which the water quality farmer acquire more profits and vice versa. Our results also evaluate the cost effectiveness related the credit stacking policies that may depend on the carbon price, water quality trading cap.

Keywords: Environmental Economics, Credit Stacking Policy, Production Complementarity, Game Theory

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1 Introduction

Markets for ecosystem services represent a frontier for science, policy, and management. These markets may establish financial incentives for production or creation, or demand for "environmental credits" or off-sets necessary under regulations regarding mitigation of environmental impacts. This frontier, then, creates an ambiguity that motivates calls to constrain the functioning of environmental markets. A particular form for constraint concerns what may be called "credit stacking" or "double dipping" (Cooley and Olander, 2011; Fox, 2008). In ecosystem service market, credit *stacking* generally refer to situation where the providers of ecosystem service credits are allowed to sell different types of credits in separate markets for each type, even as these credits might derive from a single entrepreneurial action, likely on a single parcel of land. With credit stacking permitted, credit production may overlap spatially for different services.

Woodward (2011) paper offers a carefully-structured theoretical and quantitative/simulation evaluation relating to the economic implications of credit stacking policy. In Woodward's model, not allowing credit stacking is framed as a single market institution (SM) while allowing credit stacking is framed a multiple market institution (MM). Farmers' technology choices involve the choices on complementarity and specialization parameters in the joint production function. Valcu et al. (2013) is most relevant to our study as they look at the agricultural soils to be a source for both carbon sequestration and water quality improvement; however their research differs from ours in significant ways. Particularly, in this paper, we consider the possible impact of famers' market choice when SM restriction is imposed.

In this research, we explore the implications when only the regional credit is traded under the cap-and-trade framework while the price for the global credit is exogenous. This "mixed" style market institution has not been well studied; however, it is a possible market environment that credit producers may face when multiple markets can be established. Montero (2001) considered a permit system that can accommodate multiple pollutant under regulations; however, the differences between an exogenous credit and endogenous credit are not recognized in the model. In this study, we use the water quality credit and carbon sequestration credit as an illustrative example, realizing when a global market exists for the carbon credit, a single credit producer, usually a farmer, who has no influence in the market price. We focus on farmers' market choices in the SM, i.e., which market they decide to participant when there is an restriction on the number of credit types they can sell; we also evaluate farmers's profitability in the MM and further evaluate the cost effectiveness of the credit stacking policy when a regional credit market and a global credit market coexist.

Our results show that in the SM institution, depending on the market price for the carbon credit (assume everything else is fixed, such as the trading cap for the water quality credit), five different scenarios might happen as the carbon price increases; farmers specialized in water quality improvement (water quality farmers) and farmers specialized in carbon sequestration (carbon farmers) will choose to participant in different markets. Interestingly, we find that under a certain price range, it is possible that carbon farmers will choose to sell in the water quality market and the water quality farmers will choose to produce in the carbon market. In the MM institution, both types of farmers can participate in the water quality market as well as the carbon market. We find there exists a certain price threshold for the carbon price, under which the water quality farmers acquire more profits and vice versa. Our results also reveal that the relative advantages of the credit stacking policy, depending on the carbon price, water quality trading cap.

The rest of the paper is organized as follows. Section 2 provides a theoretical framework that set up an analytical basis that differentiates SM and MM, largely based Woodward (2011) and Liu and Swallow (2013) . Section 3 evaluates social efficiency tradeoffs based on the model . Section 4 concludes the paper by discussing policy implications from the results and the model limitations.

2 The Basic Model

In this section, we present the theoretical model in a general case, where multiple credits are produced simultaneously by a credit producer; some credit prices are exogenous, such as the carbon sequestration credit price, while the market prices for other types of credits are determined endogenously, such as the equilibrium price of the water quality credit under a cap-and-trade framework. Farmers are the main providers of various kinds of environmental credits used to offset pollution. We consider a situation where there are I farmers producing J types of credits. The farmers are denoted by the set $\mathcal{I} = \{i \in \mathbb{N}^+ : i = 1, ..., I\}$ and the types of credit are denoted by the set $\mathcal{J} = \{j \in \mathbb{N}^+ : j = 1, ..., J\}$.

There are two broad category of credits: one category of credits is regulated under a cap and trade framework, which we denote as $\mathcal{J}_1 = \{j \in \mathbb{N}^+ : j = 1, ..., \tilde{j}\}$; the other category is traded in more or less competitive market, which we denote as $\mathcal{J}_2 = \{j \in \mathbb{N}^+ : j = \tilde{j} + 1, ..., J\}$. Thus, the number of endogenous credits is $|\mathcal{J}_1|$, and the number of exogenous credits is $|\mathcal{J}_2|$. The market price vector for various types of credit can denoted as $\mathcal{P} = \{j \in \mathbb{N}^+ : p_{\tilde{j}+1}, p_{\tilde{j}+2}, ..., p_J\}$, where p_j is the price for type j credit. Farmer i has a two-dimensional production technology, which we denote as $t_i = (\gamma_i, \eta_i) \in \mathcal{T}$ that determines the individual production frontier. In our context, the production technology $\mathcal{T}$ is fixed. The role of the regulator is to choose a cap vector $\mathcal{A} = (A_1, A_2, .., A_{\tilde{j}})$ such that all the credits traded in the market are subject to the cap. Therefore, the amount of credits produced is determined by the market cap $\mathcal{A}$, the current technology $\mathcal{T}$, and the market price $\mathcal{P}$. Let a_{ij} be the amount of type j pollutant that farmer i chooses to abate (or the amount of credit the farmer choose to produce). Thus, farmer i's cost is determined by the production technology and the amount of credits produced, specific, we use $g(a_{ij})$ to denote the production cost of farmer i producing a_{ij} amount of credit j. Note the farmers' cost, profit is also a function of the regulatory cap, market price and production technology. We assume that a certain extent of complementarity exists in farmers' production technology; that is, given a fixed quantity of producing one pollutant, a cost minimization farmer will "automatically" produce some amount of another credit. The total social benefits are additively separable in each type of credit, for simplicity, assume $B(A) = \sum_j B_j(A_j)$. The regulator can set an optimal cap for each credit $\hat{A}_j$ to induce a first-best solution. In this section, we first briefly introduce the basic model, and then consider how the outcome might be different if farmer can choose different management practices. In the basic model, the production technology is constant, exogenously determined, then relax this assumption so that farmers can choose a different management practice which will influence the production function.

2.1 The planner's problem

Optimally, the regulator only need to choose a cap vector $\mathcal{A}$ for those traded under a cap-and-trade framework, so that the net social benefit is maximized:

$$A_j^* \in \arg\max \left(\sum_{j=1}^{J} B_j(A_j) - \sum_{i=1}^{I} g_i(a_{ij}), s.t. A_j = \sum_{i=1}^{I} a_{ij} \right)$$

The optimal emission cap A^* can be found from the first order condition:

$$B_j'(A_j^*) = \frac{\partial g_i(a_{ij})}{\partial a_{ij}},\ i \in \mathcal{I}, j \in \mathcal{J}_1.$$

The regulator needs to have full information on both cost and benefit sides of the credit markets in order to set the optimal cap. In reality, the regulator might not set the cap optimally, which can lead to distortion of credit production. Since the benefit of credit is hard to quantify, we only assume an arbitrary regulatory choice to investigate the cost effectiveness of the two market institutions in a partial equilibrium framework.

2.2 Allowing Credit Stacking, Multiple Market (MM)

In the multiple market, the farmer can sell all types of credits produced from the same land. We assume a rational farmer who pursues the maximized profit by choosing the amount produced for each type. In the equilibrium state, the market price for exogenous credits and endogenous credits are both fixed; in this situation, the farmer maximizes profits:

$$max \sum_{j=1}^{m} p_j a_{ij} - g_i(a_i).$$

The FOC (first order condition) for a_{ij} is:

$$p_j = \frac{\partial g_i(a_i)}{\partial a_{ij}},\ \forall i \in \mathcal{I}, j \in \mathcal{J}.$$

The solution for the optimal choice of production amount a_{ij} is consistent with the solutions in the regulator's problem if the cap is set optimally, also, the equilibrium market price for the exogenous credit should satisfy the above equation as well.

2.3 Not Allowing Credit Stacking, Single Market (SM)

Under the SM approach, the farmer can only choose one type of credit to sell. Thus, the farmer will maximize her profit by 1) choosing the type of credit 2) the amount of credit to sell. In this situation, the farmer maximizes profits:

$$\max_{j} \{\max_{a_{ij}} (p_j a_{ij} - g_i(a_{ij}))\}.$$

where $g(a_{ij})$ is the cost function. The decision to participate in market j will be optimal if

$$p_s a^*_{ij} - g_i(a^*_{ij}) \geq p_s a^*_{ik} - g_s(a^*_{is}), \forall s \neq j,\ s, j \in \mathcal{J}.$$

Note that the optimal solution is not uniquely identified citepwoodward2011double. Also, the total credits produced would be higher than the regulatory cap due to the complementarity in production if the cost minimization of producing one type credit would also produce some "by product" of other credits, which is considered as the origin of the stacking issue .

3 The Coexistent of Regional Credits and Global Credits

In the section, we explore the implications when only one type of the credit (water quality credit) is traded under the cap-and-trade framework while the credit price for the other type is fixed (carbon sequestration credit), i.e., $|\mathcal{J}_1| = |\mathcal{J}_2| = 1$. We use the water quality credit and carbon credit as an illustrative example only realizing when a global market exists for the carbon, an individual farmer has no influence in the market price. The price for carbon can fluctuate a lot and the change of the market price can certainly influence farmers' production decisions, as well as their technology choices. Thus, we focus on the influence of the carbon price on farmers' technology choice and how the choices may vary in a SM or MM institution.

3.1 Equilibrium In the SM

Still, assume the two credits market coexist and the technology choices are fixed for now and two representative farmers, the cost functions for the carbon farmer k and the water quality famer h are:

$$g_k = \frac{\eta}{2}c_k^2 + \frac{1/\eta}{2}w_k^2 + \gamma_w c_k w_k$$

$$g_h = \frac{1/\eta}{2}c_h^2 + \frac{\eta}{2}w_h^2 + \gamma_c c_h w_h$$

with the same notation as before. Given the water quality credit cap $\hat{A}$ and the market price of carbon $\hat{p}$, the problem face by farmer k (who is specialized in the carbon credit) is:

$$\max_{j_1 \ or \ j_2} \ \hat{p}c_k + p_2 w_k - \left(\frac{\eta}{2}c_k^2 + \frac{1/\eta}{2}w_k^2 + \gamma_c c_k w_k\right),$$

where j_1, j_2 denote farmers' market choices. If a farmer chooses j_1, which is the carbon sequestration credit market, she will only get revenue from producing carbon credit while producing some water quality credits, however without being able to sell these water quality credits. Interpretations on choosing the water quality market is similar. First we derive the conditions under which the carbon producer will sell the carbon market and the water quality market, respectively.

The problem face by the farmer h (who is specialized in water quality credit) is:

$$\max_{j_1 \ or \ j_2} \ \hat{p}c_h + p_2 w_h - \left(\frac{1/\eta}{2}c_h^2 + \frac{\eta}{2}w_h^2 + \gamma_w c_h w_h\right)$$

Note there are four possible scenarios: 1) both types choose to sell in the carbon market; 2) both types choose to sell in the water quality carbon market; 3) farmers specialized in carbon offsetting sell credits in the carbon market while the other type sell credits in the water quality market and, maybe less likely, 4) farmers specialized in carbon offsetting sell credits in the water quality market while the other type sell credits in the carbon market. The range of the market price for carbon, $\hat{p}$, may determine which of the above four scenarios may happen.

Assume the carbon farmers will sell in the carbon market, the optimal production can be expressed as:

$$c_k^{SM|C} = \frac{\hat{p}}{(1-\gamma_c^2)\eta}, w_k^{SM|C} = \frac{-\gamma_c \hat{p}}{1-\gamma_c^2},$$

and

$$c_k^{SM|W} = \frac{-\gamma_c p_2}{1-\gamma_c^2}, w_k^{SM|W} = \frac{p_2 \eta}{1-\gamma_c^2}$$

if the carbon farmers sell in the water quality market in the single market institution.

Similarly, when the water quality farmers sell in the water market, the optimal production is:

$$c_h^{SM|W} = \frac{-\gamma_w p_2}{1-\gamma_w^2}, w_h^{SM|W} = \frac{p_2}{(1-\gamma_w^2)\eta},$$

and

$$c_h^{SM|C} = \frac{\hat{p}\eta}{1-\gamma_w^2}, w_h^{SM|C} = \frac{-\gamma_w \hat{p}}{1-\gamma_w^2}$$

if the water quality farmers sell in the carbon market in the single market institution.

Denote the profit of carbon selling in the carbon market as $\pi_{C|C}$, the profit of the carbon farmer selling in the water quality market while the water quality farmer is selling in the carbon market is denoted as $\pi_{C|WC}$, the profit of the carbon farmer selling in the water quality market while the water quality farmer is also selling in the water quality market is denoted as $\pi_{C|WW}$. Similarly, denote the profit of water quality farmers by $\pi_{W|C}$, $\pi_{W|WC}$ and $\pi_{W|WW}$. Thus, we have,

$$\pi_{C|C} = \frac{\hat{p}^2}{2(1-\gamma_c^2)\eta},$$

regardless the choice of water quality farmer. If water quality farmers sell in the water market [1],

$$\pi_{C|WW} = \frac{A^2 \eta}{2(1-\gamma_c^2)\left(\frac{1}{(1-\gamma_w^2)\eta} + \frac{\eta}{1-\gamma_c^2}\right)^2}$$

If water quality farmers sell in the carbon market,

$$\pi_{C|WC} = \frac{A^2(1-\gamma_c^2)}{2\eta}$$

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[1] For convenience, assuming in the equilibrium farmers of either type will choose the same complementarity level for now.

For the water quality farmers, if they sell in the water market and the carbon farmers sell in the carbon market, the profit is:

$$\pi_{W|WC} = \frac{\eta A^2(1-\gamma_w^2)}{2}$$

If the water quality farmers sell in the water market and the carbon farmers sell in the water quality market as well, the profit for a water quality farmer is:

$$\pi_{W|WW} = \frac{A^2}{2(1-\gamma_w^2)\left(\frac{1}{(1-\gamma_w^2)\eta} + \frac{\eta}{1-\gamma_c^2}\right)^2 \eta}$$

If water quality sell in the carbon market, the profit is:

$$\pi_{W|C} = \frac{\eta \hat{p}^2}{2(1-\gamma_w^2)}.$$

Assume all the complementarity levels are fixed for now. Now the water quality farmer has two choice: participating in the carbon market or participating in the water quality market; the carbon farmer also has two choices: participating in the carbon market or participating in the water quality market. Thus, there are four possible outcomes, depending the market price of carbon (assuming all else fixed). Here we apply the Nash Equilibrium concept, and derive the price range of carbon price under which each situation is likely to emerge. For example, the conditions that both types of famers selling in the water quality market is: 1) given the choice of water quality farmer (the water quality farmer sell in the water quality market), the carbon farmer cannot get a higher profit by choosing to sell in the carbon market; 2) given the choice of the carbon farmer (in this case, the carbon farmer is selling the water quality market), the water quality farmer cannot get a higher profit by choosing to sell in the carbon market. We expect this situation is likely only if the market price for carbon is extremely low. Similarly, we can use such constraints to derive the range of carbon price for the remaining three situations. As discussed before, consider the following four situations:

- Situation 1: both types sell in the carbon market, which implies $\pi_{C|C} \geq \pi_{C|WC}$ and $\pi_{W|C} \geq \pi_{W|WC}$. Thus, we have:

$$\frac{\hat{p}^2}{2(1-\gamma_c^2)\eta} \geq \frac{\hat{A}^2(1-\gamma_c^2)}{2\eta}$$

and

$$\frac{\eta\hat{p}^2}{2(1-\gamma_w^2)} \geq \frac{\eta\hat{A}^2(1-\gamma_w^2)}{2}.$$

We can get

$$\hat{p} \geq \max\{A(1-\gamma_w^2), A(1-\gamma_c^2)\}.$$

- Situation 2 both types sell in the water quality market, which implies $\pi_{C|WW} \geq \pi_{C|C}$ and $\pi_{W|WW}(\gamma) \geq \pi_{W|C}(\gamma)$. Thus, we have:

$$\frac{A^2\eta}{2(1-\gamma_c^2)\left(\frac{1}{(1-\gamma_w^2)\eta}+\frac{\eta}{1-\gamma_c^2}\right)^2} \geq \frac{\hat{p}^2}{2(1-\gamma_c^2)\eta}$$

and

$$\frac{A^2}{2(1-\gamma_w^2)\left(\frac{1}{(1-\gamma_w^2)\eta}+\frac{\eta}{1-\gamma_c^2}\right)^2\eta} \geq \frac{\eta\hat{p}^2}{2(1-\gamma_w^2)}.$$

Thus, we can infer:

$$\hat{p} \leq \frac{A}{\frac{1}{(1-\gamma_w^2)\eta^2}+\frac{1}{1-\gamma_c^2}}$$

- Situation 3 carbon farmers sell in the carbon market, and water quality farmers sell in the water quality market, which implies $\pi_{C|C} \geq \pi_{C|WW}$ and $\pi_{W|WC} \geq \pi_{W|C}$. Thus, we have:

$$\frac{\hat{p}^2}{2(1-\gamma_c^2)\eta} \geq \frac{A^2\eta}{2(1-\gamma_c^2)\left(\frac{1}{(1-\gamma_w^2)\eta}+\frac{\eta}{1-\gamma_c^2}\right)^2}$$

and

$$\frac{\eta\hat{A}^2(1-\gamma_w^2)}{2} \geq \frac{\eta\hat{p}^2}{2(1-\gamma_w^2)}.$$

Thus, we have:

$$\hat{p} \in \left[\frac{A}{\frac{1}{(1-\gamma_w^2)\eta^2} + \frac{1}{1-\gamma_c^2}}, A(1-\gamma_w^2) \right],\ when\ \eta^2 < \frac{1}{1-\frac{1-\gamma_w^2}{1-\gamma_c^2}};$$

$$\hat{p} \in \emptyset,\ when\ \eta^2 \geq \frac{1}{1-\frac{1-\gamma_w^2}{1-\gamma_c^2}}.$$

- Situation 4 carbon farmers sell in the water quality market, and water quality farmers sell in the carbon market, which implies $\pi_{C|WC} \geq \pi_{C|C}$ and $\pi_{W|C} \geq \pi_{W|WW}$. Thus, we have:

$$\frac{\hat{A}^2(1-\gamma_c^2)}{2\eta} \geq \frac{\hat{p}^2}{2(1-\gamma_c^2)\eta},$$

and

$$\frac{\eta\hat{p}^2}{2(1-\gamma_w^2)} \geq \frac{A^2}{2(1-\gamma_w^2)\left(\frac{1}{(1-\gamma_w^2)\eta} + \frac{\eta}{1-\gamma_c^2}\right)^2 \eta}.$$

We can get:

$$\hat{p} \in \left[\frac{A}{\frac{1}{1-\gamma_w^2} + \frac{\eta^2}{1-\gamma_c^2}}, A(1-\gamma_c^2) \right],\ when\ \eta^2 > 1 - \frac{1-\gamma_c^2}{1-\gamma_w^2};$$

$$\hat{p} \in \emptyset,\ when\ \eta^2 \leq 1 - \frac{1-\gamma_c^2}{1-\gamma_w^2}.$$

Let $\hat{p}_1 = \frac{A}{\frac{1}{(1-\gamma_w^2)\eta^2}+\frac{1}{1-\gamma_c^2}}$, $\hat{p}_2 = \frac{A}{\frac{1}{1-\gamma_w^2}+\frac{\eta^2}{1-\gamma_c^2}}$, $\hat{p}_3 = A(1-\gamma_w^2)$ and $\hat{p}_4 = A(1-\gamma_c^2)$. From the above analyses, we can infer that $\hat{p}_1 < \hat{p}_2 < \hat{p}_3$.

Case 1: When $\gamma_w = \gamma_c$, $\hat{p}_1 < \hat{p}_2 < \hat{p}_3 = \hat{p}_4$. These three different price levels divide the entire region into four pieces. Thus, if

- $\hat{p} \leq \hat{p}_1$, both types will sell in the water quality market (Situation 2) .

- $\hat{p} \in [\hat{p}_1, \hat{p}_2]$, carbon famers will choose produce in the carbon market and water quality farmers will choose to produce in the water quality market (Situation 3).

- $\hat{p} \in [\hat{p}_2, \hat{p}_{3(4)}]$, carbon famers will choose produce in the carbon market and water quality farmers will choose to produce in the water quality market or vice verse (Situation 3 or Situation 4).
- $\hat{p} \geq \hat{p}_{3(4)}$, both types will sell in the carbon market (Situation 1).

Case 2: When $\gamma_w > \gamma_c$, $\hat{p}_1 < \hat{p}_2 < \hat{p}_3 < \hat{p}_4$. These four different price levels lead to five regions. Thus, if

- $\hat{p} \leq \hat{p}_1$, both types will sell in the water quality market (Situation 2) .
- $\hat{p} \in [\hat{p}_1, \hat{p}_2]$, carbon famers will choose produce in the carbon market and water quality farmers will choose to produce in the water quality market (Situation 3).
- $\hat{p} \in [\hat{p}_2, \hat{p}_3]$, carbon famers will choose produce in the carbon market and water quality farmers will choose to produce in the water quality market or vice verse (Situation 3 or Situation 4).
- $\hat{p} \in [\hat{p}_3, \hat{p}_4]$, carbon farmers will choose to sell in the water quality market and water quality farmers will choose to produce in the carbon market (Situation 4).
- $\hat{p} \geq \hat{p}_4$, both types will sell in the carbon market (Situation 1).

Case 3: When $\gamma_w < \gamma_c$, $\hat{p}_1 < (\hat{p}_2, \hat{p}_4) < \hat{p}_3$. The relative magnitude between $\hat{p}_2$ and $\hat{p}_4$ is uncertain. We need to more detailed discussion.

Case 3-1: If $\eta > \sqrt{1 - \frac{1-\gamma_c^2}{1-\gamma_w^2}}$, then $\hat{p}_2 < \hat{p}_4$, the result is the same as *Case 2*.

Case 3-2: If $\eta < \sqrt{1 - \frac{1-\gamma_c^2}{1-\gamma_w^2}}$, then $\hat{p}_1 < \hat{p}_4 < \hat{p}_2 < \hat{p}_3$. Thus, if

- $\hat{p} \leq \hat{p}_1$, both types will sell in the water quality market (Situation 2) .
- $\hat{p} \in [\hat{p}_1, \hat{p}_3]$, carbon famers will choose produce in the carbon market and water quality farmers will choose to produce in the water quality market (Situation 3).
- $\hat{p} \geq \hat{p}_4$, both types will sell in the carbon market (Situation 1).

To summarize, there are only two general scenarios. The first general scenario includes *Case 1*, *Case 2* and *Case 3-1*: *Case 1* can be regarded as a special case of *Case 2*, also *Case 2* and *Case 3-1* have identical solutions. The second general scenario includes *Case 3-2*, which is different than the other cases.

3.2 A Graphical Analysis on Farmers' Market Choice in SM

The above equations do not help us understand how different scenarios may happen in a straightforward way. Figure 1 provides more intuitions behind the mathematical equations and analyzes the strategic interactions more carefully. Such considerations are important to further understand the potential restrictions imposed by the SM. Figure 1 depicts farmers' profit levels depending on their market choice, i.e., whether they choose to sell credits in the water quality market or the carbon market. The horizontal axis is the market price for carbon, which is treated an exogenous variable. The vertical axis stands for a farmer's profit level. The dashed red curves are the profit of the carbon farmer; the black solid curves are the profit of the water quality farmer. We split the range of carbon price according to four price points, $\hat{p}_1$, $\hat{p}_2$, $\hat{p}_3$ and $\hat{p}_4$, defined as before, and the horizontal axis is divided into five regions. We use *Case 2* (and *Case 3-1*) as an illustrative example since it encompasses the most complicated situations. Under each price region, the two types of farmers may interact with each other strategically and thus result in different profits. As before, we use $\pi_{C|C}$, $\pi_{C|WW}$, $\pi_{C|WC}$ and $\pi_{W|C}$, $\pi_{W|WC}$, $\pi_{W|WW}$ to denote the possible profit level, depending on farmers' choices.

When $\hat{p} < \hat{p}_1$, the market price for carbon is extremely low, we expect that both farmers sell in the water quality market. In Figure 1, $\hat{p}_1$ is decided by the intersection of the profit curve when the carbon farmer selling in the carbon market and the profit curve of the carbon farmer when both carbon and water quality farmers are selling in the water quality market. In this region, we can rank the six profit levels,

$$\pi_{C|WC} > \pi_{W|WC} > \pi_{W|WW} > \pi_{C|WW} > \pi_{C|C} > \pi_{W|C}.$$

In Table 1, we list farmers' profit depending on their own choice, as well as the other farmer. From Table 1, if the water quality farmer chooses to participate in carbon market, the carbon farmer will choose to sell in the water quality market, thus we underline $\pi_{C|WC}$ since $\pi_{C|WC} > \pi_{C|C}$, as in the above profit rank condition; if the water quality farmer chooses to participate in water quality market, the carbon farmer will still chose the water quality market, thus we underline $\pi_{C|WW}$ since

$\pi_{C|WW} > \pi_{C|C}$; similarly, if the carbon farmer chooses to participate in carbon market, the water quality farmer will chooses the water quality market, thus we underline $\pi_{W|WC}$ since $\pi_{W|WC} > \pi_{W|C}$; if the carbon farmer chooses to participate in water quality market, the water quality farmer will choose the water quality market, thus we underline $\pi_{W|WW}$ since $\pi_{W|WW} > \pi_{W|C}$. Thus, the only equilibrium choice is both types of farmers participant in the water quality market, given that the market price for carbon is extremely low (relative to the water quality cap).

As the market price for carbon increases and passes $\hat{p}_1$, the carbon farmer will get a higher price by selling in the carbon market, than selling water quality credit together with water quality farmer. The profits rank is now,

$$\pi_{C|WC} > \pi_{W|WC} > (\pi_{W|WW}, \pi_{C|C}) > (\pi_{C|WW}, \pi_{W|C}).$$

where $(\pi_{W|WW}, \pi_{C|C})$ and $(\pi_{C|WW}, \pi_{W|C})$ denote that the relative magnetite between $\pi_{W|WW}$ and $\pi_{C|C}$, or between $\pi_{C|WW}$ and $\pi_{W|C}$ is uncertain. However, this will not create ambiguity regarding farmers' market choice since the profit level for the same (type of) farmer can be ranked. From Table 2, we can infer the equilibrium choice is when the water quality farmer sells in the water quality market and the carbon farmer sells in the carbon market. Both carbon farmers and water quality farmers will get a larger profit. The water quality farmer get a higher profit because he is selling the water quality credit alone and the water quality price will increase.

As the carbon price passes $\hat{p}_2$, which is the intersection of the profit curve of the water quality farmer selling in the carbon market and the profit curve of the water quality farmer when both types are selling in the water quality market, the rank of profits changes to the following,

$$\pi_{C|WC} > (\pi_{W|WC}, \pi_{C|C}) > \pi_{W|C} > \pi_{W|WW} > \pi_{W|C}.$$

From Table 3, we find two equilibrium outcomes: either the water quality farmer sells in the water quality market and the carbon farmer sells in the carbon market or *vice verse*. The price for water quality will further increase when the carbon farmer is selling in the water quality market; in this equilibrium (cell $\underline{(\pi_{C|WC}, \pi_{W|C})}$ in Table 3), carbon farmer will get a higher profit while the water farmer will get lower profit compared to the alternative equilibrium. However, in both equilibrium, neither type can get a higher profit by unilateral deviation.

When the carbon price rises above $\hat{p}_3$, which is the intersection of the profit curve that the water quality farmer selling in the carbon market and the profit curve of the water quality farmer when only the water quality farmer is selling in the water quality market, the profit rank changes to:

$$\pi_{C|WC} > \pi_{C|C} > \pi_{W|C} > \pi_{W|WC} > \pi_{W|WW} > \pi_{C|WW}.$$

Table 4 shows that the only equilibrium is when the water quality farmer sells in the carbon market and carbon farmers sells in the water quality market. This is a very interesting result, since both types of farmers will choose to sell in the market in which one is *not* specialized. This is similar to the counter-signaling result in the signaling games (Feltovich et al., 2002; Araujo et al., 2007). If this situation happens, we expect a significant loss as farmers are incentivized to focus production on a more costly credit. This can be a quite generic result when credit stacking is not allowed, which we will discuss later.

When the carbon price is higher to $\hat{p}_4$, which is the intersection of the profit curve that the carbon farmer selling in the carbon market and the profit curve of the carbon farmer when only the carbon farmer is selling in the water quality market,

$$\pi_{C|C} > \pi_{W|C} > \pi_{C|WC} > \pi_{W|WC} > \pi_{W|WW} > \pi_{C|WW}.$$

Table 5 shows that both farmers will choose to sell in the carbon market, as expected. In this situation, both types will sell in the carbon market; there is no supply of water quality credits.

From Section 3.1, we can conclude that if $\gamma_w < \gamma_c$ and $\eta > \sqrt{1 - \frac{1-\gamma_c^2}{1-\gamma_w^2}}$, then $\hat{p}_4 < \hat{p}_2$. In this case, the water quality farmer selling in the carbon market and the carbon farmer selling water quality market is not possible. Figure 2 shows the different areas of technology choices (a combination of the specialization level, η, and the complementarity level, γ) that may lead to different market choices when the credit stacking is not allowed. The horizontal axis is the γ_c^2, the squared term of the carbon farmer's complementarity choice. The horizontal axis is the γ_c^2, the squared term of the water quality farmer's the complementarity choice. A higher γ^2 indicates a more complementary production technology. In Area 1, regardless of the specialization technology choice η, the profit levels is shown in Figure 1, conditional on different market entry choice. In Area 2, different profit levels is shown in Figure 3, as the when the two types become more specialized (a large η^2), the Area 2 shrinks while the Area 1 expands. We choose five different specialization level, $\eta_1^2 = 0$, $\eta_2^2 = 0.25$, $\eta_3^2 = 0.5$, $\eta_4^2 = 0.75$ and $\eta_5^2 = 1$ to illustrate the relative change of Area 1 and Area 2 as the specialization level changes. From Figure 2, we can see that when η^2 is close to 1, the "reverse selection" is least likely to happen. As η^2 increases, which indicate that as the two types of farmers become less specialized, the Area 1 expands; when $\eta^2 = 1$, which means when the cost functions are symmetric in the specialization level, the "reverse selection" is always possible, regardless of farmers' complementarity technologies.

Figure 3 shows the situation when $\hat{p}_1 < \hat{p}_4 < \hat{p}_2 < \hat{p}_3$. The equilibrium choices are the same when $\hat{p} \in (0, \hat{p}_1)$. When $\hat{p} > \hat{p}_3$, both types will sell in the carbon market. When $\hat{p} \in (\hat{p}_1, \hat{p}_4]$, the equilibrium outcome is that the water quality farmer sells in the water quality market and carbon farmers will sell in the carbon market. When $\hat{p} \in (\hat{p}_4, \hat{p}_3]$, the equilibrium outcome is the same: the water quality farmer sells in the water quality market and carbon farmers will sell in the carbon market. Note the situations in Figure 3 are only possible when the technology parameters are in Area 2, as shown in Figure 2.

3.3 Equilibrium In the MM

Still, assume the two credits market coexist and the technology choices are fixed, the cost functions for the carbon farmer g_k and the water quality famers g_h are:

$$g_k = \frac{\eta}{2}c_k^2 + \frac{1/\eta}{2}w_k^2 + \gamma_c c_k w_k,$$

$$g_h = \frac{1/\eta}{2}c_h^2 + \frac{\eta}{2}w_h^2 + \gamma_w c_h w_h,$$

using the same notation as before. Given the water quality credit cap $\hat{A}$ and the market price of carbon $\hat{p}$, the problem face by farmer k (who is specialized in the carbon credit) is:

$$\max_{c_k, w_k} \hat{p} c_k + p_2 w_k - (\frac{\eta}{2} c_k^2 + \frac{1/\eta}{2} w_k^2 + \gamma_c c_k w_k)$$

The problem face by the farmer h (who is specialized in water quality credit) is:

$$\max_{c_h, w_h} \hat{p} c_h + p_2 w_h - (\frac{1/\eta}{2} c_h^2 + \frac{\eta}{2} w_h^2 + \gamma_w c_h w_h)$$

We can also derive the optimal production for each type of farmers:

$$c_k^{MM} = \frac{\begin{vmatrix} \hat{p} & \gamma_c \\ p_2 & \frac{1}{\eta} \end{vmatrix}}{\begin{vmatrix} \eta & \gamma_c \\ \gamma & \frac{1}{\eta} \end{vmatrix}} = \frac{\frac{\hat{p}}{\eta} - p_2 \gamma_c}{1 - \gamma_c^2}, w_k^{MM} = \frac{\begin{vmatrix} \eta & \hat{p} \\ \gamma & p_2 \end{vmatrix}}{\begin{vmatrix} \eta & \gamma_c \\ \gamma & \frac{1}{\eta} \end{vmatrix}} = \frac{\eta p_2 - \gamma_c \hat{p}}{1 - \gamma_c^2}$$

$$c_h^{MM} = \frac{\begin{vmatrix} p_2 & \eta \\ \hat{p} & \gamma \end{vmatrix}}{\begin{vmatrix} \gamma_w & \eta \\ \frac{1}{\eta} & \gamma_w \end{vmatrix}} = \frac{\eta \hat{p} - \gamma_w p_2}{1 - \gamma_w^2}, w_h^{MM} = \frac{\begin{vmatrix} \gamma_w & p_2 \\ \frac{1}{\eta} & \hat{p} \end{vmatrix}}{\begin{vmatrix} \gamma_w & \eta \\ \frac{1}{\eta} & \gamma_w \end{vmatrix}} = \frac{\frac{p_2}{\eta} - \gamma_w \hat{p}}{1 - \gamma_w^2}$$

Therefore, the profit of carbon farmers is:

$$\pi_c = \frac{\frac{1}{2\eta} \hat{p}^2 - \gamma_c \hat{p} p_2 + \frac{\eta}{2} p_2^2}{1 - \gamma_c^2}.$$

The profit of the water quality farmer is:

$$\pi_w = \frac{\frac{\eta}{2} \hat{p}^2 - \gamma_w \hat{p} p_2 + \frac{1}{2\eta} p_2^2}{1 - \gamma_w^2}.$$

where p_2 is:

$$p_2 = \frac{A + (\frac{\gamma_c}{1-\gamma_c^2} + \frac{\gamma_w}{1-\gamma_w^2})\hat{p}}{\frac{\eta}{1-\gamma_c^2} + \frac{1}{\eta(1-\gamma_w^2)}}.$$

When $\gamma_c = \gamma_r$, the profit functions are symmetrical and the water quality credit price is:

$$p_2 = \frac{A(1-\gamma^2) + 2\gamma\hat{p}}{\eta + \frac{1}{\eta}}.$$

More generally, the profit of the carbon farmer can be rewritten as:

$$\pi_c = \hat{p}^2 * \frac{\frac{1}{2\eta} - \gamma_c(\frac{p_2}{\hat{p}}) + \frac{\eta}{2}(\frac{p_2}{\hat{p}})^2}{1-\gamma_c^2};$$

the profit of the water quality farmer can be rewritten as:

$$\pi_w = \hat{p}^2 * \frac{\frac{\eta}{2} - \gamma_w(\frac{p_2}{\hat{p}}) + \frac{1}{2\eta}(\frac{p_2}{\hat{p}})^2}{1-\gamma_w^2}.$$

Therefore, the necessary condition for $\pi_w > \pi_c$ is:

$$\pi_w - \pi_c = \hat{p}^2 * \left[-\frac{\frac{1}{2\eta} - \gamma_c(\frac{p_2}{\hat{p}}) + \frac{\eta}{2}(\frac{p_2}{\hat{p}})^2}{1-\gamma_c^2} + \frac{\frac{\eta}{2} - \gamma_w(\frac{p_2}{\hat{p}}) + \frac{\eta}{2}(\frac{p_2}{\hat{p}})^2}{1-\gamma_w^2} \right] > 0.$$

Rearrange the above equation, we can get:

$$\left[\frac{1-\gamma_c^2}{2\eta} - \frac{\eta(1-\gamma_w^2)}{2}\right](\frac{p_2}{\hat{p}})^2 + \left[\gamma_c(1-\gamma_w^2) - \gamma_w(1-\gamma_c^2)\right](\frac{p_2}{\hat{p}}) + \left[\frac{\eta}{2}(1-\gamma_c^2) - \frac{1}{2\eta}(1-\gamma_w^2)\right] > 0.$$

Note that since

$$\begin{aligned} & [\gamma_c(1-\gamma_w^2) - \gamma_w(1-\gamma_c^2)]^2 - 4\left[\tfrac{1-\gamma_c^2}{2\eta} - \tfrac{\eta(1-\gamma_w^2)}{2}\right]\left[\tfrac{\eta}{2}(1-\gamma_c^2) - \tfrac{1}{2\eta}(1-\gamma_w^2)\right] \\ = \; & (1-\gamma_c^2)(1-\gamma_w^2)[(\gamma_w+\gamma_c)^2 - (\eta + \tfrac{1}{\eta})^2)] \\ \leq \; & (1-\gamma_c^2)(1-\gamma_w^2)[(\gamma_w+\gamma_c)^2 - 2] \\ \leq \; & 0, \end{aligned}$$

we can conclude that:

- when $\frac{1-\gamma_c^2}{2\eta} - \frac{\eta(1-\gamma_w^2)}{2} > 0$, or $\eta < \sqrt{\frac{1-\gamma_c^2}{1-\gamma_w^2}}$, $\pi_w > \pi_c$.

- when $\frac{1-\gamma_c^2}{2\eta} - \frac{\eta(1-\gamma_w^2)}{2} < 0$, or $\eta > \sqrt{\frac{1-\gamma_c^2}{1-\gamma_w^2}}$, $\pi_w < \pi_c$.

- when $\frac{1-\gamma_c^2}{2\eta} - \frac{\eta(1-\gamma_w^2)}{2} = 0$, or $\eta = \sqrt{\frac{1-\gamma_c^2}{1-\gamma_w^2}}$: if $\gamma_c = \gamma_w$, then $\pi_w < \pi_c$; if $\gamma_c > \gamma_w$, then exists $\hat{p}^*$ such that when $\hat{p} < \hat{p}^*$, $\pi_w > \pi_c$ and *vice versa*.

Figure 4 shows the relative profitability between the carbon farmer and the water quality farmer, depending the combination of different technology choices. Similar to Figure 2, Figure 4 shows the different areas of technology choices (mainly complementarity level) that result different profit levels for the water quality farmer and the carbon farmer. The horizontal axis is the γ_c^2, the squared term of the carbon farmers the complementarity choices. The horizontal axis is the γ_c^2, the squared term of the water quality farmers the complementarity choices. A higher γ^2 indicates a more complementary production technology. In Area 1, the profit of carbon farmer is higher than the profit of the water quality farmer. In Area 2, the profit of carbon farmer is lower than the profit of the water quality farmer. Note the when the two types become more specialized (a larger η^2), the Area 2 expands while the Area 1 shrinks. We choose five different specialization level, $\eta_1^2 = 0$, $\eta_2^2 = 0.25$, $\eta_3^2 = 0.5$, $\eta_4^2 = 0.75$ and $\eta_5^2 = 1$ to illustrate the relative change of Area 1 and Area 2 as the specialization level changes.

4 Implications on Credit Production and Cost Effectiveness

4.1 The Price for the Water Quality Credit

The price for the carbon credit is treated as an exogenous variable, which is a less concern; the water quality credit price can be different in SM, depending on the equilibrium market choices, and also water quality price in the SM can be different from the MM. We will abuse notations a little bit here to highlight the differences between SM and MM. In the SM, there are three possible price levels for the water quality credit, they are $p_w^w = \frac{A}{\frac{1}{\eta(1-\gamma_w^2)}}$, $p_w^{wc} = \frac{A}{\frac{\eta}{1-\gamma_c^2}+\frac{1}{\eta(1-\gamma_w^2)}}$ and $p_w^c = \frac{A}{\frac{\eta}{1-\gamma_c^2}}$, with $p_w^{wc} < p_w^w < p_w^c$; note that $p_w^{wc} = \hat{p}_2\eta$, $p_w^w = \hat{p}_3\eta$ and $p_w^c = \hat{p}_4\eta$. The super script w, wc and c denote the situation when only the water quality farmer sells in the water quality market, both carbon and water quality farmers sell in the water quality market, and when only the carbon farmer sells in the water quality market. In the SM, the water quality credit price will not change with the change of carbon credit price.

In the MM, the water quality credit price is

$$p_w^{MM} = \frac{A + (\frac{\gamma_c}{1-\gamma_c^2} + \frac{\gamma_w}{1-\gamma_w^2})\hat{p}}{\frac{\eta}{1-\gamma_c^2} + \frac{1}{\eta(1-\gamma_w^2)}},$$

which is lower than p_w^{wc}, the water quality credit price in the SM when both carbon and water quality farmers choose to sell in the water quality market, i.e., when the carbon credit price is extremely low. Take the first order derivatives of $p_w^{MM}(\hat{p})$ with respect to $\hat{p}$, we can conclude that:

$$\frac{\partial p_w^{MM}(\hat{p})}{\partial \hat{p}} = \frac{\frac{\gamma_c}{1-\gamma_c^2} + \frac{\gamma_w}{1-\gamma_w^2}}{\frac{\eta}{1-\gamma_c^2} + \frac{1}{\eta(1-\gamma_w^2)}} < 0.$$

The above inequality shows that the water quality credit price will increase as the carbon price decreases in the MM. Also, since the following inequality always holds:

$$p_w^{wc} < p_w^{w} < p_w^{c}.$$

Therefore, the water quality credit price in the MM is always lower than the water quality credit price in the SM, thus,

$$p_w^{MM} < p_w^{SM}.$$

4.2 The Total Quantity Produced for the Carbon Credit and the Water Quality Credit

In the MM institution, the total water quality credits produced equals

$$Q_w^{MM} = A$$

while the total carbon sequestration credit produced is

$$Q_c^{MM} = \hat{p}[\tilde{J} - (\gamma_c + \gamma_w)(1 + \gamma_c\gamma_w)\tilde{K}] - (1 - \gamma_w^2)(1 - \gamma_c^2)A\tilde{K},$$

where

$$\tilde{J} = \frac{1}{\eta(1 - \gamma_c^2)} + \frac{\eta}{1 - \gamma_w^2} > 0$$

and

$$\tilde{K} = \eta[\frac{\gamma_c}{\eta^2(1 - \gamma_w^2) + (1 - \gamma_c^2)^2} + \frac{\gamma_w}{\eta^2(1 - \gamma_w)^2 + (1 - \gamma_c^2)}] < 0.$$

Since $\frac{\partial Q_C^{MM}}{\partial A} > 0$ and $\frac{\partial Q_C^{MM}}{\partial \hat{p}} > 0$, either an increase in the carbon price and an increase in the water quality credit cap will increase the total carbon credits produced. In the SM institution, depending the carbon price, the total water quality credits and the carbon credit can be different.

In Figure 1,

- $\hat{p} \leq \hat{p}_1$, $Q_w^{SM} = A$ and $Q_c^{SM} = -p_w^{wc}(\frac{\gamma_c}{1-\gamma_c^2} + \frac{\gamma_w}{1-\gamma_w^2})$;
- $\hat{p} \in [\hat{p}_1, \hat{p}_2]$, $Q_w^{SM} = A - \frac{\gamma_c\hat{p}}{1-\gamma_c^2}$ and $Q_c^{SM} = \frac{\hat{p}}{(1-\gamma_c^2)\eta} - \frac{\gamma_c p_2^w}{1-\gamma_c^2}$;
- $\hat{p} \in [\hat{p}_2, \hat{p}_3]$, $Q_w^{SM} = A - \frac{\gamma_c\hat{p}}{1-\gamma_c^2}$ and $Q_c^{SM} = \frac{\hat{p}}{(1-\gamma_c^2)\eta} - \frac{\gamma_c p_2^w}{1-\gamma_c^2}$, or $Q_w^{SM} = A + \frac{\hat{p}\eta}{1-\gamma_w^2}$ and $Q_c^{SM} = \frac{\hat{p}\eta}{1-\gamma_c^2} + \frac{p_w^c\eta}{1-\gamma_c^2}$;
- $\hat{p} \in [\hat{p}_3, \hat{p}_4]$, $Q_w^{SM} = A + \frac{\hat{p}\eta}{1-\gamma_w^2}$ and $Q_c^{SM} = \frac{\hat{p}\eta}{1-\gamma_c^2} + \frac{p_w^c\eta}{1-\gamma_c^2}$;
- $\hat{p} \geq \hat{p}_4$, $Q_w^{SM} = -\hat{p}(\frac{\gamma_c}{1-\gamma_c^2} + \frac{\gamma_w}{1-\gamma_w^2})$ and $Q_c^{SM} = \frac{\hat{p}}{(1-\gamma_c^2)\eta} - \frac{\gamma_c p_2^w}{1-\gamma_c^2} = \hat{p}\tilde{J}$;

where $p_w^w = \frac{A}{\frac{1}{\eta(1-\gamma_w^2)}}$, $p_w^{wc} = \frac{A}{\frac{\eta}{1-\gamma_c^2} + \frac{1}{\eta(1-\gamma_w^2)}}$ and $p_w^c = \frac{A}{\frac{\eta}{1-\gamma_c^2}}$.

In Figure 3, the situation where the carbon farmer selling in the water quality market while the water quality farmer selling in the carbon market is not possible, thus:

- $\hat{p} \leq \hat{p}_1$, $Q_w^{SM} = A$ and $Q_c^{SM} = -p_w^{wc}(\frac{\gamma_c}{1-\gamma_c^2} + \frac{\gamma_w}{1-\gamma_w^2})$;
- $\hat{p} \in [\hat{p}_1, \hat{p}_3]$, $Q_w^{SM} = A - \frac{\gamma_c\hat{p}}{1-\gamma_c^2}$ and $Q_c^{SM} = \frac{\hat{p}}{(1-\gamma_c^2)\eta} - \frac{\gamma_c p_2^w}{1-\gamma_c^2}$;
- $\hat{p} \geq \hat{p}_3$, $Q_w^{SM} = -\hat{p}(\frac{\gamma_c}{1-\gamma_c^2} + \frac{\gamma_w}{1-\gamma_w^2})$ and $Q_c^{SM} = \frac{\hat{p}}{(1-\gamma_c^2)\eta} - \frac{\gamma_c p_2^w}{1-\gamma_c^2} = \hat{p}\tilde{J}$;

where $p_w^w = \frac{A}{\frac{1}{\eta(1-\gamma_w^2)}}$ and $p_w^{wc} = \frac{A}{\frac{\eta}{1-\gamma_c^2}+\frac{1}{\eta(1-\gamma_w^2)}}$.

Not surprisingly, for the total water quality credits produced, we find

$$Q_w^{SM} \geq Q_w^{MM},$$

unless the carbon price is so high that both types decide to sell the carbon market in the SM. The above inequality is due to the production complementarily: in the SM, unless both types choose to sell in the same market (either when the carbon credit price is relative low, $\hat{p} \leq \hat{p}_1$, or relative high, $\hat{p} \geq \hat{p}_{4/3}$), the total water quality credit produced will be higher than the regulated cap. The result for the total carbon credits is not as obvious. In the SM, when both types choose to sell in the carbon market ($\hat{p} \geq \hat{p}_{4/3}$), the total carbon credit produced is the highest, for simplicity, let

$$Q_c^{SM} = \hat{p}\tilde{J};$$

the total carbon credit produced in the MM is:

$$Q_c^{MM} = \hat{p}\tilde{J} \underbrace{-\underbrace{\hat{p}(\gamma_c+\gamma_w)(1+\gamma_c\gamma_w)}_{>0}\tilde{K}}_{<0} \underbrace{\underbrace{-(1-\gamma_w^2)(1-\gamma_c^2)A}_{<0}\tilde{K}}_{>0}.$$

Therefore, when

$$(1-\gamma_w^2)(1-\gamma_c^2)A < -\hat{p}(\gamma_c+\gamma_w)(1+\gamma_c\gamma_w),$$

or

$$\hat{p} > -\frac{A(1-\gamma_w^2)(1-\gamma_c^2)}{(\gamma_c+\gamma_w)(1+\gamma_c\gamma_w)},$$

the total carbon credits produced in the MM is higher than the *maximum* possible total carbon credits in the SM, and *vice versa*.

4.3 The Difference in Total Cost between SM and MM

The total cost in the MM institution is:

$$\begin{aligned} TC_{MM} &= \tfrac{\eta}{2}c_k^2 + \tfrac{1}{2\eta}w_k^2 + \gamma_c c_k w_k + \tfrac{1}{2\eta}c_h^2 + \tfrac{\eta}{2}w_h^2 + \gamma_w c_h w_h \\ &= \tfrac{\eta}{2}(c_k^{MM})^2 + \tfrac{1}{2\eta}(w_k^{MM})^2 + \gamma_c c_k^{MM} w_k^{MM} + \tfrac{1}{2\eta}(c_h^{MM})^2 + \tfrac{\eta}{2}(w_h^{MM})^2 + \gamma_w c_h^{MM} w_h^{MM} \end{aligned}$$

If the technology parameters of the cost function lead to Figure 1 (similar in Figure 3), the total cost in the SM institution is :

- $\hat{p} \leq \hat{p}_1$,

  $TC_{SM} = \frac{\eta}{2}(c_k^{SM|W})^2 + \frac{1}{2\eta}(w_k^{SM|W})^2 + \gamma_c c_k^{SM|W} w_k^{SM|W} + \frac{1}{2\eta}(c_h^{SM|W})^2 + \frac{\eta}{2}(w_h^{SM|W})^2 + \gamma_w c_h^{SM|W} w_h^{SM|W}$;

- $\hat{p} \in [\hat{p}_1, \hat{p}_2]$,

  $TC_{SM} = \frac{\eta}{2}(c_k^{SM|C})^2 + \frac{1}{2\eta}(w_k^{SM|C})^2 + \gamma_c c_k^{SM|C} w_k^{SM|C} + \frac{1}{2\eta}(c_h^{SM|W})^2 + \frac{\eta}{2}(w_h^{SM|W})^2 + \gamma_w c_h^{SM|W} w_h^{SM|W}$;

- $\hat{p} \in [\hat{p}_2, \hat{p}_3]$,

  $TC_{SM} = \frac{\eta}{2}(c_k^{SM|C})^2 + \frac{1}{2\eta}(w_k^{SM|C})^2 + \gamma_c c_k^{SM|C} w_k^{SM|C} + \frac{1}{2\eta}(c_h^{SM|W})^2 + \frac{\eta}{2}(w_h^{SM|W})^2 + \gamma_w c_h^{SM|W} w_h^{SM|W}$,

  or

  $TC_{SM} = \frac{\eta}{2}(c_k^{SM|W})^2 + \frac{1}{2\eta}(w_k^{SM|W})^2 + \gamma_c c_k^{SM|W} w_k^{SM|W} + \frac{1}{2\eta}(c_h^{SM|C})^2 + \frac{\eta}{2}(w_h^{SM|C})^2 + \gamma_w c_h^{SM|C} w_h^{SM|C}$;

- $\hat{p} \in [\hat{p}_3, \hat{p}_4]$,

  $TC_{SM} = \frac{\eta}{2}(c_k^{SM|W})^2 + \frac{1}{2\eta}(w_k^{SM|W})^2 + \gamma_c c_k^{SM|W} w_k^{SM|W} + \frac{1}{2\eta}(c_h^{SM|C})^2 + \frac{\eta}{2}(w_h^{SM|C})^2 + \gamma_w c_h^{SM|C} w_h^{SM|C}$;

- $\hat{p} \geq \hat{p}_4$,

  $TC_{SM} = \frac{\eta}{2}(c_k^{SM|C})^2 + \frac{1}{2\eta}(w_k^{SM|C})^2 + \gamma_c c_k^{SM|C} w_k^{SM|C} + \frac{1}{2\eta}(c_h^{SM|C})^2 + \frac{\eta}{2}(w_h^{SM|C})^2 + \gamma_w c_h^{SM|C} w_h^{SM|C}$.

In order to evaluate the cost effectiveness of the credit stacking policy, we compare the cost of production when the outcomes (the quantity of credits produced in SM and MM) equal in the SM and MM. $c_k^{MM} = c_k^{SM|C} + c_k^{SM|W}$, $w_k^{MM} = w_k^{SM|C} + w_k^{SM|W}$, $c_h^{MM} = c_h^{SM|C} + c_h^{SM|W}$ and $w_h^{MM} = w_h^{SM|C} + w_h^{SM|W}$. Substitute them into the total cost function for MM institution, we can get, for the carbon farmer:

$$\begin{aligned}
TC(c_k^{MM}, w_k^{MM}) &= \tfrac{\eta}{2}(c_k^{MM})^2 + \tfrac{1}{2\eta}(w_k^{MM})^2 + \gamma_c c_k^{MM} w_k^{MM} \\
&= \tfrac{\eta}{2}(c_k^{SM|C} + c_k^{SM|W})^2 + \tfrac{1}{2\eta}(w_k^{SM|C} + w_k^{SM|W})^2 + \gamma_c(c_k^{SM|C} + c_k^{SM|W})(w_k^{SM|C} + w_k^{SM|W}) \\
&= TC(c_k^{SM|C}, w_k^{SM|C}) + TC(c_k^{SM|W}, w_k^{SM|W}) \\
&+ \gamma_c(c_k^{SM|W} w_k^{SM|W} + c_k^{SM|C} w_k^{SM|C}) + \gamma_w(c_k^{SM|C} w_k^{SM|C} + c_k^{SM|W} w_h^{SM|W})
\end{aligned}$$

for the water quality farmer:

$$\begin{aligned}
TC(c_h^{MM}, w_h^{MM}) &= \tfrac{\eta}{2}(c_h^{MM})^2 + \tfrac{1}{2\eta}(w_h^{MM})^2 + \gamma_c c_h^{MM} w_k^{MM} \\
&= \tfrac{\eta}{2}(c_h^{SM|C} + c_h^{SM|W})^2 + \tfrac{1}{2\eta}(w_h^{SM|C} + w_h^{SM|W})^2 + \gamma_w(c_h^{SM|C} + c_k^{SM|W})(w_h^{SM|C} + w_h^{SM|W}) \\
&= TC(c_h^{SM|C}, w_h^{SM|C}) + TC(c_h^{SM|W}, w_h^{SM|W}) \\
&+ \gamma_c(c_h^{SM|W} w_h^{SM|W} + c_h^{SM|C} w_h^{SM|C}) + \gamma_w(c_h^{SM|C} w_h^{SM|C} + c_h^{SM|W} w_h^{SM|W})
\end{aligned}$$

Therefore, we can conclude that when $c_k^{MM} = c_k^{SM|C} + c_k^{SM|W}$, $w_k^{MM} = w_k^{SM|C} + w_k^{SM|W}$, $c_h^{MM} = c_h^{SM|C} + c_h^{SM|W}$ and $w_h^{MM} = w_h^{SM|C} + w_h^{SM|W}$, then

$$TC(c_k^{MM}, w_k^{MM}) \;<\; TC(c_k^{SM|W}, w_k^{SM|W}) + TC(c_k^{SM|C}, w_k^{SM|C});$$

and

$$TC(c_h^{MM}, w_h^{MM}) \;<\; TC(c_h^{SM|W}, w_h^{SM|W}) + TC(c_h^{SM|C}, w_h^{SM|C}).$$

The above two inequalities ensure that the unit cost per credit is smaller in the MM, compared to SM. Even though the SM may produce extra credits "for free" due to production complementarity, it is always possible that MM produces the same amount of credits with a smaller unit cost. Though the relative price of carbon and water quality can influence the cost effectiveness of credit production in the SM, it is easy to see that, when carbon price and water quality price equals, $TC(c_k^{SM|W}, w_k^{SM|W}) < TC(c_k^{SM|C}, w_k^{SM|C})$ and $TC(c_h^{SM|W}, w_h^{SM|W}) > TC(c_h^{SM|C}, w_h^{SM|C})$, which means that, it is less cost effective for the carbon farmer selling the water quality market, than the carbon farmer selling in the carbon market. As discussed before, this misalignment is possible in the SM; we can expect that in such situations, the society be worse off as a whole since the cost needed to produce the same amount of credits is higher. This inefficiency is largely created by the limitation on farmer's market choice and exaggerated by the profit maximizing goal from farmers. Note that, when water quality cap is high compared to the carbon market price, it is possible that $TC(c_k^{SM|W}, w_k^{SM|W}) > TC(c_k^{SM|C}, w_k^{SM|C})$, or if the carbon price is relative high to the water quality cap, we may have $TC(c_h^{SM|W}, w_h^{SM|W}) < TC(c_h^{SM|C}, w_h^{SM|C})$. To see why this is case, since

$$\begin{aligned} TC(c_k^{SM|C}, w_k^{SM|C}) &= \tfrac{\eta}{2}c_k^2 + \tfrac{1/\eta}{2}w_k^2 + \gamma_c c_k w_k \\ &= (\tfrac{\hat{p}}{1-\gamma_c^2})^2(\tfrac{1}{2\eta} + \gamma_c^2\tfrac{1/\eta}{2} - \gamma_c^2\tfrac{1}{\eta}) \\ &= \tfrac{\hat{p}^2}{2\eta(1-\gamma_c^2)} \end{aligned}$$

and

$$\begin{aligned} TC(c_k^{SM|W}, w_k^{SM|W}) &= \tfrac{\eta}{2}c_k^2 + \tfrac{1/\eta}{2}w_k^2 + \gamma_c c_k w_k \\ &= (\tfrac{p_2}{1-\gamma_c^2})^2(\gamma_c^2\tfrac{\eta}{2} + \tfrac{\eta}{2} - \gamma_c^2\eta) \\ &= \tfrac{\eta p_2^2}{2(1-\gamma_c^2)} \end{aligned}$$

If $TC(c_k^{SM|W}, w_k^{SM|W}) > TC(c_k^{SM|C}, w_k^{SM|C})$, then $\frac{\hat{p}}{p_2} < \eta$. When the carbon type farmer sells in the water quality market, the water quality price can take two possible values: $p_2^{wc} = \frac{A}{\frac{\eta}{1-\gamma_c^2}+\frac{1}{\eta(1-\gamma_w^2)}}$ and $p_2^c = \frac{A}{\frac{\eta}{1-\gamma_c^2}}$. Thus, when $p_2 = \frac{A}{\frac{\eta}{1-\gamma_c^2}+\frac{1}{\eta(1-\gamma_w^2)}}$, then $\hat{p}\left(\frac{\eta}{1-\gamma_c^2} + \frac{1}{\eta(1-\gamma_w^2)}\right) < A\eta$. When $p_2 = \frac{A}{\frac{\eta}{1-\gamma_c^2}}$, then $\hat{p}\left(\frac{\eta}{1-\gamma_c^2}\right) < A\eta$. Therefore, when.

$$\frac{A}{\hat{p}} > \frac{1}{1-\gamma_c^2} + \frac{1}{\eta^2(1-\gamma_w^2)},$$

or

$$\frac{A}{\hat{p}} > \frac{1}{1-\gamma_c^2},$$

it is less cost effective for the carbon farmer selling the carbon market than the carbon farmer selling in the water quality market. This result suggests the misalignment may be a more cost effective way to produce credit in the SM compared to the situation where each farmer is only sell in the market in which one is more specialized. In the water quality market, similarly, we can derive,

$$\begin{aligned} TC(c_h^{SM|C}, w_h^{SM|C}) &= \tfrac{1}{2\eta}c_k^2 + \tfrac{\eta}{2}w_k^2 + \gamma_w c_h w_h \\ &= \tfrac{\eta\hat{p}^2}{2(1-\gamma_w^2)} \end{aligned}$$

and

$$\begin{aligned} TC(c_h^{SM|W}, w_h^{SM|W}) &= \tfrac{\eta}{2}c_h^2 + \tfrac{1/\eta}{2}w_h^2 + \gamma_w c_h w_h \\ &= \tfrac{p_2^2}{2\eta(1-\gamma_w^2)}. \end{aligned}$$

If

$$\frac{A}{\hat{p}} < \frac{1}{1-\gamma_c^2} + \frac{1}{\eta^2(1-\gamma_w^2)},$$

or

$$\frac{A}{\hat{p}} < \frac{1}{1-\gamma_w^2},$$

it is less cost effective for the water quality farmer selling the water quality market than the water quality farmer selling in the carbon market.

5 Conclusions and Discussion

This research shows how the restriction on market choice (such as the limitation imposed by the SM institution) can be misaligned with farmers' types; we find it is possible, when carbon price is high but not too high, the equilibrium outcome is that the carbon farmer chooses to sell in the water quality market and the water quality farmer chooses to sell the carbon market. As we demonstrate later, such misalignment can be a costly way to reach the abatement target. According to our specification, the MM is always more cost effectiveness compared to the SM, however, it is possible that, when the cap is set incorrect at a suboptimal level (Woodward, 2011), SM will be better than the MM in terms of cost effectiveness. Also, our research demonstrates how the choice on cap of one credit and the equilibrium market price of another credit can influence farmers' production choices respectively/together. These linkages are important when a more balanced ecosystem service production is pursued. Currently, most of the ecosystem markets focus on the provision of only one credit, largely captured by the SM institutional setting, which may lead to over-provision of one credit, at the cost of suppressing the production of other types of credits. The SM can also lead to undesired outcome scenarios where the credit producers are incentivized to produce credits in a less cost effectiveness manners; some ecosystem markets focus on providing a bundle of credits, such the wetland credit, which is hard to measure and often the rules are ambiguous. In this situation, it is possible that a farmer, who is enrolled in a wetland mitigation program, can also benefit from the carbon credit. On the other hand, if the credit producers are allowed to sell all types of credits, even some of credits require no additional effort, farmers will be incentivized to choose a point on the production frontier, where he slope of the tangency line equals here the price ratio of different credit types. Such a production is more balanced in the since that the market will help decide the relative value of each credit type, and the resulting equilibrium production will be efficient if the cap is chosen efficiently and if the market price truly reflect the marginal social benefit of the credit, both for a local credit such as water quality and a global credit such as carbon sequestration.

To establish functioning and coherent multiple credit markets be can particularly challenging. If the cap-and-trade framework is applied to one of the credit, an inappropriate choice on the cap will lead to distortion in the multiple credit market, same as in the single market. Further, due to intrinsic connections between multiple markets, the distortion of an inappropriate chosen cap be larger than in a SM. Also, the process of of establishing multiple market may require significant efforts from policy makers and may face may legislation challenges. One particular challenges may come from polluters. The establishment of multiple credit markets require specific regulations on these credits, and such regulations will likely increase the abatement cost of producers. However, when credit producers are allowed to provide all types of credits, the per unit cost of a credit will likely to decrease, such as a lower water quality price in the MM, as we showed in the previous section. Though the polluters have to comply to multiple regulations, the overall cost is uncertain. The overall abatement achieved from multiple, coexisting credit markets will decrease due to the production complementarity, the precise reason why some researchers may favor a SM approach. But the additional abatement in SM cause a much higher cost. Here we show that the complementarity will actually lead to more abatement in the MM institution: it is always possible to achieve the same abatement objective in the MM with a strictly lower cost than achieving the same abatement goal in the SM.

We assume a specific functional form for the credit producers' iso-cost lines. This functional form captures two important technology parameters: the specialization level, which reflects the heterogeneity among different types of credit producers; the complementarity level, which reflects the ability to produce other credits "for free" when maximizing profit for one type of credit. We expect most of results can be applied to a more general functional form as long as the two technology parameters similarly determine the shape of the iso-cost function and the positive complementarily exists. Note that in our context, the credit producers are not able to change the technology parameters. If the credit producers have some flexibility, Liu and Swallow (2013) demonstrate that such flexibility will only increase the cost effectiveness of the MM, since the farmers tend to choose a more complementary production technology in the MM, which is source that results in difference between SM and MM, as we showed in the previous section.

The problem of designing a functional environmental credit trading system is of crucial interest to environmental economists. Current discussions and debates surround the credit stacking policy only reflect one aspect of potential challenges. A full understanding of the credit trading system may need more researches from a mechanism design perspective, and an optimal institution can be regional specific or even a mixed combination of current trading institutions, such as a mix of SM and MM. On the other hand, perhaps bigger challenges are more practical considerations, such as how to address the credit producers' participation problem, how to make sure monetary compensation offers the right incentive, how to impose appropriate regulations on polluters and enforce compliance standards; all of these can be as important as the search for a theoretically better trading mechanism. More researches in these two areas can complement each other and help establish credit trading markets that can improve environmental quality, generate more revenues/profits for credit producers and reduce pollution.

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Table 1: Farmers' Choices and Profits in SM, $\hat{p} \in [0, \hat{p}_1)$.

	Carbon Market	Water Quality Market
Carbon Market	$(\pi_{C\mid C},\ \pi_{W\mid C})$	$(\pi_{C\mid C},\ \underline{\pi_{W\mid WC}})$
Water Quality Market	$(\underline{\pi_{C\mid WC}},\ \pi_{W\mid C})$	$(\underline{\pi_{C\mid WW}},\ \underline{\pi_{W\mid WW}})$

Table 2: Farmers' Choices and Profits in SM, $\hat{p} \in (\hat{p}_1, \hat{p}_2)$.

	Carbon Market	Water Quality Market
Carbon Market	$(\pi_{C\mid C},\ \pi_{W\mid C})$	$(\underline{\pi_{C\mid C}},\ \underline{\pi_{W\mid WC}})$
Water Quality Market	$(\underline{\pi_{C\mid WC}},\ \pi_{W\mid C})$	$(\pi_{C\mid WW},\ \underline{\pi_{W\mid WW}})$

Table 3: Farmers' Choices and Profits in SM, $\hat{p} \in [\hat{p}_2, \hat{p}_3)$.

	Carbon Market	Water Quality Market
Carbon Market	$(\pi_{C\mid C},\ \pi_{W\mid C})$	$(\underline{\pi_{C\mid C}},\ \underline{\pi_{W\mid WC}})$
Water Quality Market	$(\underline{\pi_{C\mid WC}},\ \underline{\pi_{W\mid C}})$	$(\pi_{C\mid WW},\ \pi_{W\mid WW})$

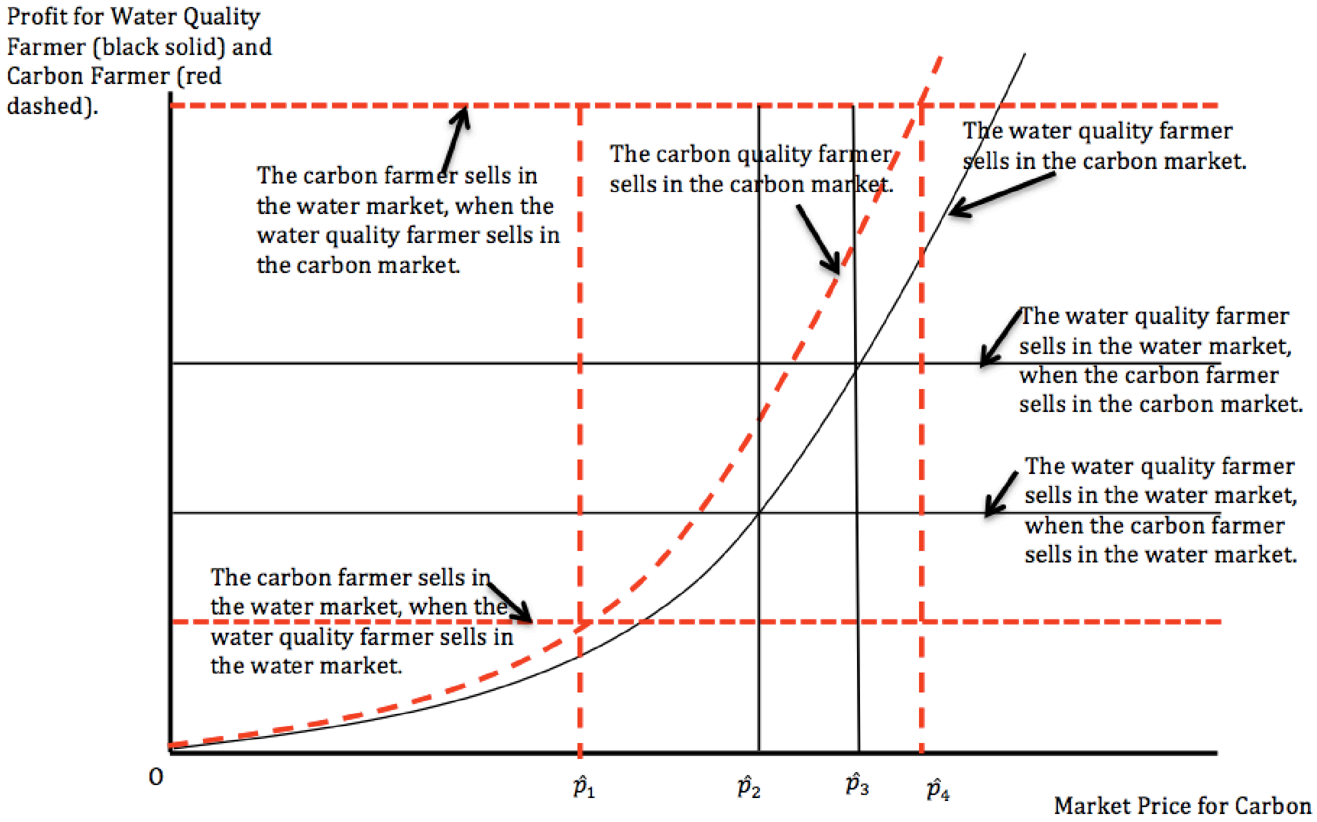
Table 4: Farmers' Choices and Profits in SM, $\hat{p} \in [\hat{p}_3, \hat{p}_4)$.

	Carbon Market	Water Quality Market
Carbon Market	$(\pi_{C\mid C},\ \underline{\pi_{W\mid C}})$	$(\underline{\pi_{C\mid C}},\ \pi_{W\mid WC})$
Water Quality Market	$(\underline{\pi_{C\mid WC}},\ \underline{\pi_{W\mid C}})$	$(\pi_{C\mid WW},\ \pi_{W\mid WW})$

Table 5: Farmers' Choices and Profits in SM, $\hat{p} > \hat{p}_4$.

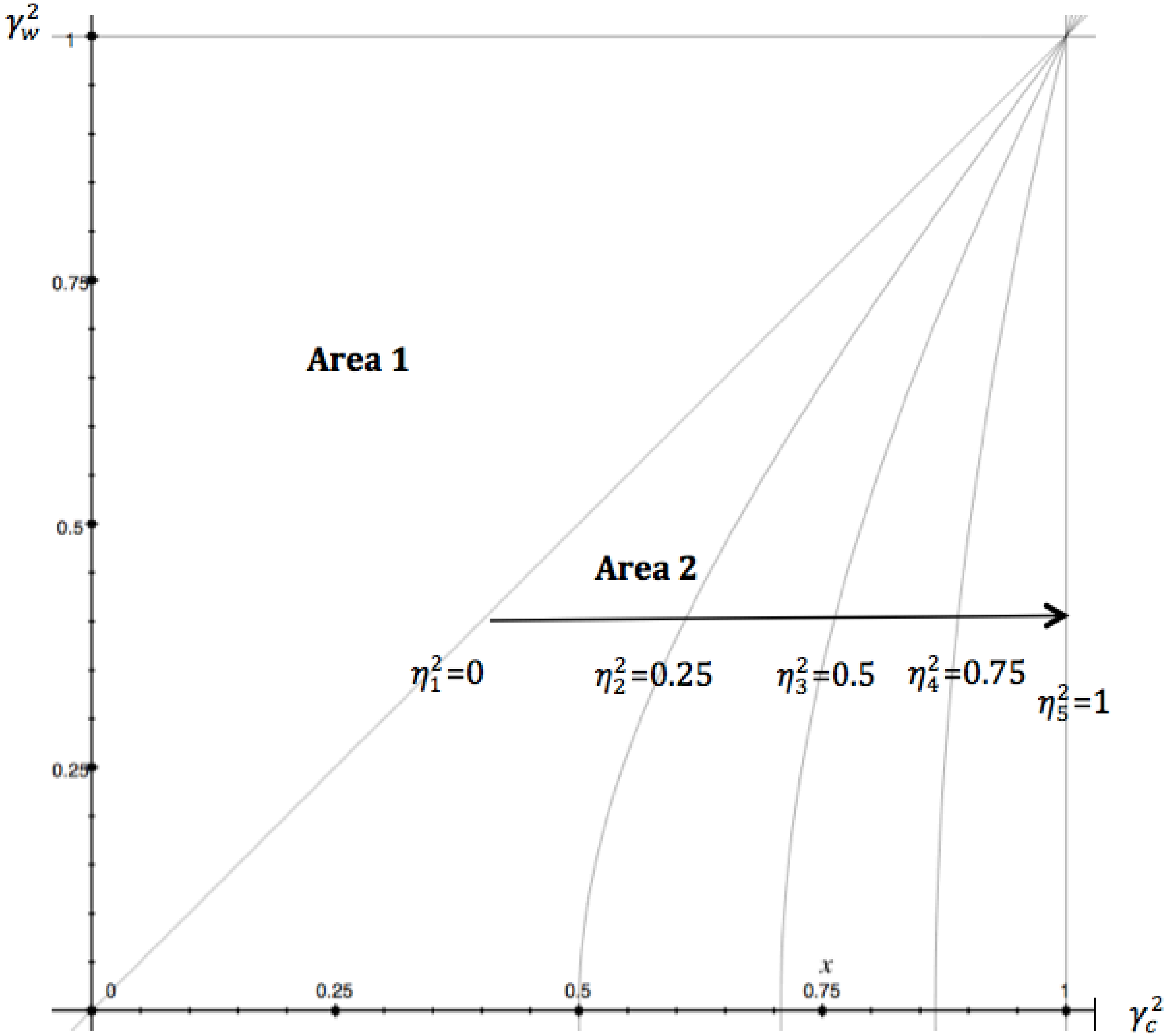
	Carbon Market	Water Quality Market
Carbon Market	$(\pi_{C\mid C},\ \pi_{W\mid C})$	$(\pi_{C\mid C},\ \underline{\pi_{W\mid WC}})$
Water Quality Market	$(\underline{\pi_{C\mid WC}},\ \pi_{W\mid C})$	$(\underline{\pi_{C\mid WW}},\ \underline{\pi_{W\mid WW}})$

Figure 1: Farmers' Profits When Credit Stacking is Not Allowed (Single Market)



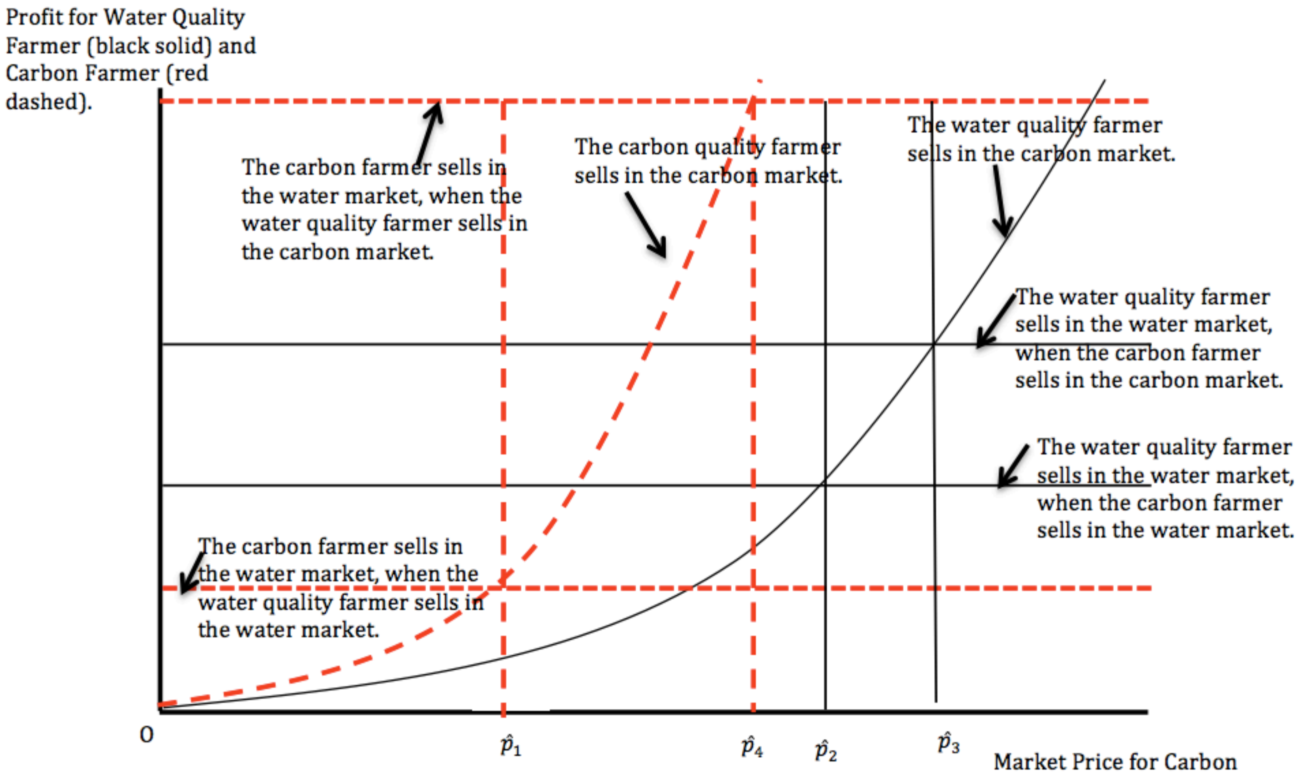
Note: This graph depicts farmers' profit levels under different market choice. The horizontal axis is the market price for carbon, which is treated an exogenous variable. The vertical axis the different profit levels. The dashed red curves are the profit of the carbon farmer; the black solid curves are the profit of the water quality farmer. We have four price points, $\hat{p}_1$, $\hat{p}_2$, $\hat{p}_3$ and $\hat{p}_4$, which divide the whole range into five regions. Under each region, the two types of farmers may interact with each other strategically and thus result in different profits. This graph corresponds to the Area 1 in Figure 2.

Figure 2: The Different Ranges of Technology Parameters in SM



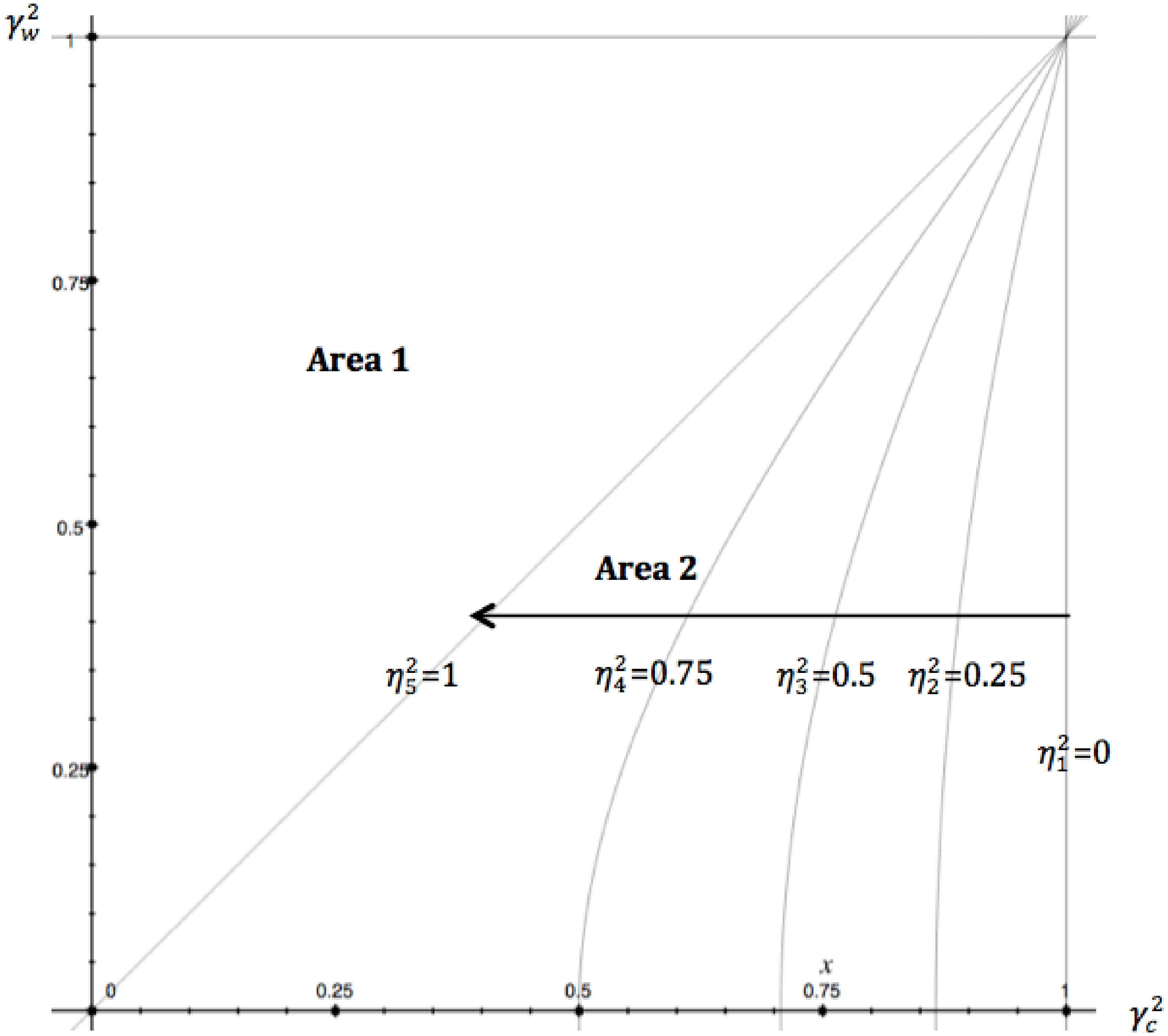
Note: This figure shows the different areas of technology choices that may lead to different market choices when the credit stacking is not allowed. The horizontal axis is the γ_c^2, the squared term of the carbon farmer' s complementarity choices. The horizontal axis is the γ_c^2, the squared term of the water quality farmer's complementarity choices. A higher γ^2 indicates a more complementary production technology. In Area 1, the profit levels is shown in Figure 1, conditional on different market entry choice. In Area 2, different profit levels is shown in Figure 3, note the when the two types become more specialized (a larger η^2), the Area 2 shrinks while the Area 1 expands. We choose five different specialization level, $\eta_1^2 = 0$, $\eta_2^2 = 0.25$, $\eta_3^2 = 0.5$, $\eta_4^2 = 0.75$ and $\eta_5^2 = 1$ to illustrate the relative change of Area 1 and Area 2 as the specialization level, η, changes.

Figure 3: Farmers' Profits When Credit Stacking is Not Allowed (Single Market)



Note: This graph depicts farmers' profit levels under different market choices. The horizontal axis is the market price for carbon, which is treated an exogenous variable. The vertical axis the different profit levels. The dashed red curves are the profit of the carbon farmer; the black solid curves are the profit of the water quality farmer. We have four price points, $\hat{p}_1$, $\hat{p}_2$, $\hat{p}_3$ and $\hat{p}_4$, which divide the whole range into five regions. In each region, the two types of farmers interact with each other strategically and result in different equilibrium profit levels. Note that $\hat{p}_2 > \hat{p}_4$, which is different from Figure 1.This graph corresponds to the Area 2 in Figure 2.

Figure 4: The Different Ranges of Technology Parameters in MM



Note: This figure shows the different areas of technology choices that result different profit levels for the water quality farmer and the carbon farmer. The horizontal axis is the γ_c^2, the squared term of the carbon farmer's complementarity choices. The horizontal axis is the γ_c^2, the squared term of the water quality farmer's complementarity choices. A higher γ^2 indicates a more complementary production technology. In Area 1, the profit of carbon farmer is higher than the profit of the water quality farmer. In Area 2, the profit of carbon farmer is lower than the profit of the water quality farmer. Note the when the two types become more specialized (a larger η^2), the Area 2 expands while the Area 1 shrinks. We choose five different specialization level, $\eta_1^2 = 0$, $\eta_2^2 = 0.25$, $\eta_3^2 = 0.5$, $\eta_4^2 = 0.75$ and $\eta_5^2 = 1$ to illustrate the relative change of Area 1 and Area 2 as the specialization level changes.

A Appendix 1