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# Topics in Establishing Environmental Markets: Performance of a Multi-Units Public Good Auction and Credit Stacking Policy

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Pengfei Liu, Ph.D.

University of Connecticut, 2016

## ABSTRACT

The purpose of my study is to better understand the current obstacles in establishing a functional environmental market. In the dissertation, I study this problem from both supply and demand sides; that is, I consider the available actions from the environmental credit suppliers, such as landowners or farmers, under different market institutions, and I also study the buyers' behaviors for a potential environmental market for a public good, such as private individuals who hold positive values toward various types of ecosystem services.

I mainly address two questions. The first question is how to raise revenue from private individuals to support an environmental market, which is discussed extensively in the first chapter. I investigate new auction approaches to support an environmental market, focusing on the differences in individuals' contribution behaviors when they are asked to support a public or common good in different auction approaches. Experimental results show that the proposed auction approaches can significantly increase the realized social surplus compared to the traditional pay-your-bids approach.

The second question is called the “credit-stacking” problem, which concerns suppliers’ choices and participation constraints when multiple environmental markets are to be established. Since environmental markets may be established at different scales (e.g., regional or global), I propose to study the impact of credit stacking when multiple environmental markets, including a regional and a global environmental market, coexist. I also study credit suppliers’ behavioral responses in different market institutions (or different policies, such as when credit stacking is allowed versus the situation when credit stacking is not allowed). In particular, I study how the behavioral responses of producers in the long run will influence the policy outcomes. I find that not allowing credit stacking is a substantial restriction against achieving social optimality and the social inefficiency loss due to such restriction could be magnified in the long run. My research on credit stacking policy is discussed in the second and third chapters.

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2016

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## APPROVAL PAGE

Doctor of Philosophy Dissertation

# Topics in Establishing Environmental Markets: Performance of a Multi-Units Public Good Auction and Credit Stacking Policy

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# Chapter 1

## Providing Multiple Units of a Public Good Using Individualized Price Auctions: Experimental Evidence

### 1.1 Introduction

Theoretical and experimental economists continue to pursue better understanding of the factors affecting incentives, choices, or behaviors that manifests free riding. Classical examples of public good provision include the construction of lighthouses to navigate ships, or building the “optimal” number of street lightings (Coase, 1974). Since uncoordinated individuals often fail to provide, or fall short of providing, the public good at a socially optimal level, researchers have sought to correct the under-provision problem by designing different provision mechanisms. An example is the widely known Vickery-Clark-Groves (VCG) mechanism, under which individuals are

incentivized (though weakly) to truthfully reveal their values for the public good (Vickrey, 1961; Clarke, 1971; Groves, 1973). However, the VCG mechanism is not budget-balancing and the auctioneer may face significant loss (Green and Laffont, 1979). Economists have demonstrated that theoretically, no other incentive mechanism can yield a higher expected social surplus than the VCG mechanism, thus making the mission of developing for an “ideal” implementation mechanism difficult (Gibbard, 1973). On the other hand, economists started to pursue Pareto improvements in a public good setting a long time ago. Expanding our current knowledge on provision mechanisms to mitigate market failures around public goods relative to various contexts can be helpful. Motivated by Lindahl (1919) and the more structured presentation from Samuelson (1954, 1955), we design several individualized price auction mechanisms and find these mechanisms can potentially increase social efficiency compared to existing public good provision mechanisms empirically, even though they lack incentive compatibility in theory. We widen the scope for practical Lindahl pricing by experimentally testing the effectiveness of several individualized price auctions (IPA) in delivering multiple units of a threshold public good.

The auction for multiple units of a private good has been studied extensively, motivated by the Federal Communications Commission spectrum auctions (Cramton, 1997; McAfee and McMillan, 1996) as well as the treasure auction (Cammack, 1991). Ausubel (2004) proposes an efficient ascending-bid auction for multiple homogenous objects that mitigate the Winner’s Curse problem from the Vickrey auction for private goods (Vickrey, 1961). In the Ausubel auction, the auctioneer first calls a price, contributors respond to the price with a quantity at that price, then the process iterates through increasing prices until there is no excess demand. A contributor pays the last announced price if the aggregated demand of other contributor’s is less than

the supply. Manelli et al. (2006) compared the Vickrey auction and Ausubel ascending auction experimentally, with common value components in individuals' valuations. Results show that under the common value case, the Vickrey auction is more efficient while the revenues are higher in the Ausubel auction. Based on a single set up with two units and two bidders, Engelmann and Grimm (2009) provide laboratory experiment results for five different multi-unit private good auctions.<sup>1</sup> Van Essen (2010) generalizes Ausubel's ascending auction to a public good environment and shows that in theory, truthful revelation of preferences is possible in a dynamic setting with a moderate information requirement.

Our proposed IPA mechanisms include the market clearing rule and the pricing rule. The marketing clearing rule determines whether we settle the auction starting from the first unit forward (Ascending-Unit Auction, or the AU) or starting from the last available unit backward (Descending-Unit Auction, or the DU). The pricing rule includes the pay-your-bids rule where each individual pays the amount she bids on all units provided, the marginal bid pricing rule where each individual pays her bid on the marginal unit (the last unit provided by the group) as well as all the other units provided, and the marginal pivotal pricing rule, where each individual pays her pivotal price on the marginal unit for all units provided. Our results suggest that the marginal pricing rules (both the marginal bid pricing and the marginal pivotal pricing) realize a higher social surplus compared to the pay-your-bids, non-marginal pricing rule. Our experimental results also show that the improvement in social surplus can be quite substantial and can be as high as 31% in the Ascending-Unit Auction using marginal bid pricing rule. The Descending-Unit Auctions do not perform better

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<sup>1</sup>Five auciton mechanisms tested include Uniform-Price Sealed-Bid Auction, Uniform-Price Open Auction, Discriminatory Auction, Vickrey Auction and Ausubel Auction.

than the Ascending-Unit Auctions due to significantly lower group contribution (more near-zero individual bids) on the first two units when six units are available for the group to support in total.

Our research is primarily motivated by the problem of searching for a simple, yet effective way to establish markets for previously non-marketable public goods. In environmental economics, payment for ecosystem services (PES) has been promoted as a promising way to protect and enhance ecosystem functions (Gómez-Baggethun et al., 2010; Farley and Costanza, 2010; Guerry et al., 2015). The U.S. Department of Agriculture established its Office for Environmental Markets in response to the 2008 Farm Bill. A desired PES mechanism shall improve the efficiency of the provision of various types of ecosystem services and environmental benefits, which are often public goods. The provision of ecosystem services are typically funded by government through distortionary taxes or through regulations. In this paper, we envision a decentralized market where the public could pay such positive externalities individually. A successful and functional ecosystem service market shall induce individuals to "buy" specific types of ecosystem services toward which they hold positive values (Uchida et al., 2007; Swallow et al., 2008). Due to the existence of free riding incentives, ordinary direct payment often results in insufficient public funds; that is, individuals may pay less than their true value for environmental benefits. In our context, we consider a public good that is provided in discrete units due to constraints on nature's production. We extend the Lindahl (1919) approach to the provision of multiple units of a threshold public good and then characterize some important features regarding this approach.

Nonetheless, the IPA mechanisms can have much wider applicability than defining the payment for environmental markets. For examples, recent development in the

“crowdfunding” industry has encouraged private provision from many individuals to donate over the internet towards a common service or a research project. In crowdfunding projects, a minimum startup cost is required and thus the total contribution needs to reach a certain threshold to provide the service or project, while such service or project can be further enhanced or expanded if the total contribution reaches a higher targeted level. In our context, the expansion of a particular project can be considered as the provision of an additional unit of public good. Our IPA mechanisms can be applied to facilitate these and other fundraising activities where the project or service carries public good properties in general.

There are few experimental studies on the multiple units public good provision. Bagnoli et al. (1992) investigates the public goods provision in a multiple units context and compares experimental results with theoretical predictions. Corazzini et al. (2015) conducted public good experiments that were motivated by charitable contributions to investigate the effect of the charity number on individual donation. Liu et al. (2016) study the provision of multiple units of a threshold public good with different group structures combined with rebate rules. Our framework is similar to Bagnoli et al. (1992) where individuals are asked to provide multiple units of a threshold public good through private contributions. As envisioned from Lindahl’s framework, the IPA mechanisms are intended to resolve the price and quantity endogenously, with a minimum of a priori information about the likely equilibrium in supply and demand.

This paper focuses on the pragmatic issues that are of potential interest to environmental market proposers, charity organizations, and crowdfunding companies. We do not fully characterize equilibrium individual bidding strategies under different mechanisms; such exercises can be enormously useful for developing alternative market institutions that can accommodate the provision of multiples units or levels



of public goods. As a first step, we focus on the revenue and efficiency comparisons among different provision mechanisms through a sequence of lab experiments. One of the central issues surrounding the multiple units of a private good (i.e., divisible good) is the revenue comparison between the discriminatory and uniform price auctions. The discriminatory auction has been the most widely used in practice, though the U.S. started adopting uniform-price auctions for Treasury Bonds. In this sense, our pay-your-bids (or the “pay-as-bid” in some literature) pricing rule is essentially the discriminatory price auction used in auctions for private divisible goods, while our marginal bid pricing rule resembles the uniform-price auctions studied in auctions for private divisible goods. We further explore a new version of the uniform-price auction where individuals pay only the pivotal price on the marginal unit for all units provided, which we call the marginal pivotal price auction. In the discriminatory auction, different prices are paid for by the same individual for different units (e.g., see Bartolini and Cottarelli (1997) for a survey study on the use of discriminatory auction used in selling Treasury Bonds). In a uniform-price auction, each individual pays the same price for the price calculated for the marginal unit. In the private divisible good case, Hortacsu and McAdams (2010) find that switching from a discriminatory auction to a uniform price (or the Vickrey auction) would not increase the seller’s revenue significantly, while the bidders’ expected surplus can increase no more than 0.02% from a structural model followed by the counterfactual analyses. Researchers are primarily concerned with the seller’s revenue in private multiunit auctions. Theoretically, the seller’s revenue in the private good auction context between the discriminatory and uniform price auction might depend on the realization of bidder valuations (Ausubel and Cramton, 2004). Several papers have also developed empirical strategies to address the discreteness problem when comparing the

seller's revenue (Wolak, 2007; Kastl, 2011). In our paper, we place equal emphasis on the consumers' (or the bidders') surplus, the seller's (or the producer's) net revenue as well as the overall social efficiency. Our paper tests several comparable mechanisms in providing a public good and find the marginal bid rule (similar to the uniform price in the private good case) can significantly increase the total social surplus.

The paper is organized as follow. Section 2 describes the provision mechanisms. Section 3 discusses contribution incentives and offers several numerical examples for selected provision mechanisms. Section 4 describes the experimental designs and procedures. Section 5 presents the experimental results and discusses their implications. Section 6 concludes.

## 1.2 Provision Mechanisms

The IPA mechanisms include two components: 1) the market clearing rule, which determines whether a unit of the public good is provided as well as the number of units that can be provided, and 2) the pricing rule, which determines how much each individual has to pay based on her or others' bid(s). Assume that in our context, there are  $I$  individuals asked to support a total of up to  $J$  units of public good with constant marginal cost  $C$  through voluntary contributions.<sup>2</sup> Each individual is indexed by  $i \in \{1, \dots, I\}$ , and each unit of the public good is indexed by  $j \in \{1, \dots, J\}$ . Individuals are asked to bid toward each unit of the public good simultaneously. Let  $v_i^j$  be the individual  $i$ 's value toward public good unit  $j$ . Individual  $i$ 's net profit is denoted as  $\pi_i$ . Thus, we can express the total bids on unit  $j$  as  $B_j = \sum_i b_i^j$ . Similar to

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<sup>2</sup>We assume constant provision cost for simplicity. Our methods can be easily generalized to an increasing marginal provision cost or a decreasing marginal provision cost. However, the social welfare implication, especially the allocation of the realized social surplus would differ.

a multi-units auction in a private good setting (Vickrey, 1961), we assume that each individual has a non-decreasing marginal value for each unit of public good. Thus, for all individuals, the marginal benefit curve satisfies  $v_i^k \geq v_i^j$  whenever  $k < j$ .

Below we propose two market clearing rules and two pricing rules that constitute the framework of the individualized price auctions. For comparison purposes, we use the pay-your-bids mechanism as the baseline, where each individual simply pays the amount they offer to contribute to each unit that is delivered. The pay-your-bids approach has been studied in past experiments. For example, Bagnoli et al. (1992) provide the experimental results on multiple units public good provision using a similar pay-your-bids mechanism and find that the overall contributions do not comply with the successively undominated perfect equilibrium (Bagnoli and Lipman, 1989), which is a refined equilibrium solution concept that eliminates inefficient Nash equilibria. Our market clearing rules and pricing rules create an IPA that differs from the pay-your-bids approach studied by Bagnoli et al. (1992), though such rules are built within the provision point framework (with a money back guarantee on non-provided units) for a multiple units environment.

### 1.2.1 Market Clearing Rules

The market clearing rule determines whether each unit of the public good is provided, and therefore the number of public good units provided, depending on the group contribution profile.

### Ascending-Unit Auction (AU)

In the ascending-unit auction, we compare the total bids from a group of individuals with the cost of the public good, starting from the first unit. If a group's total offers on the first unit is higher or equals to the cost of the first unit, we continue to compare the total offer on the second unit with the cost of the second unit, and so on. We will stop when the total offer for a unit is smaller than the unit cost. For example, if the total offer on the first unit, second unit and third unit are all higher than the cost, but the total offer on the fourth unit is smaller than cost of the fourth unit, we will provide three units. Therefore, the ascending-unit rule can be mathematically expressed as

$$g = \begin{cases} 0 & \text{if } B_1 < C \\ j & \text{if } B_k \geq C, B_{j+1} < C, \forall k \leq j, \end{cases} \quad (1.1)$$

where  $B_k = \sum_i b_i^k$ . Note that in order to provide  $j$  units, the total offer on *each* of the units 1, 2, ...,  $j$  must be higher than the corresponding unit cost; otherwise, the auction process will stop when the total offer of a unit falls below the cost.

### Descending-Unit Auction (DU)

In the descending-unit auction, we compare the total bids from a group with the cost of the public good, starting from the last unit available, the unit  $J$ . If the group's total offer on the last unit is higher or equal to the cost for the last unit, we will provide all  $J$  units; if the total offer is smaller than the cost of the last unit, we will move on to compare the total offer on the second-to-last unit, or the unit  $J-1$ , with the cost of that unit, we will provide all  $J-1$  units if the total offer is higher and continue to the  $(J-2)$ th unit if we fail, and so on. We will stop when the total offer for a unit is at

least as large as the unit cost. For example, if the total offer on the  $J$ th unit,  $(J-1)$ th unit and  $(J-2)$ th unit are all lower than the cost, but the offer on the  $(J-3)$ th unit is larger than its cost, we will provide  $J-3$  units in total. Therefore, the number of units provided by the group is

$$g = \begin{cases} 0 & \text{if } B_k < C, \forall k \leq J \\ j & \text{if } B_j \geq C, B_k < C, \forall k > j \end{cases} \quad (1.2)$$

with  $B_k = \sum_i b_i^k$ . Comparing the AU auction and the DU auction, we find that if  $K$  units of public good are provided in the AU auction, at least  $K$  units will be provided in the DU auction, assuming the same group contribution profile; the reverse is not true as the AU auction requires a more stringent condition to provide more units. For example, consider the profile of total offers on 5 units of public good is  $\{60, 40, 20, 30, 10\}$ , and the cost is constant at 30; 2 units of public good can be supported from the AU while 4 units can be supported from the DU auction.

### 1.2.2 Pricing Rules

Pricing rules determine individual cost and payoff. We consider three pricing rules: the first one is called the pay-your-bids auction, wherein each individual pays exactly the amount she bids when a unit is provided. This pricing rule is similar to the provision point mechanism (with no rebate and with money back guarantee) in a single unit provision (Marks and Croson, 1998; Spencer et al., 2009; Rondeau et al., 1999, 2005). The second pricing rule is the individualized price auction using marginal bids, wherein each individual pays the same price for all the units provided, and the price equals one's bid on the last unit provided. The third is the individualized price auction using the marginal pivotal price, wherein each individual still pays the same

price for all the units provided, however, the price is now based on the pivotal price calculated from the last unit provided. In all cases, the last unit  $j$  provided is given the application of equation (1.1) or (1.2) , such that  $g = j$  or  $g = 0$  .

### **Pay-your-bids Auction (PYB)**

In the PYB rule, each individual pays exactly the amount she bids if a unit is provided. Let  $t_i$  denote the amount an individual has to pay contingent on the number of units being provided. Then, we have:

$$t_i = \begin{cases} 0 & \text{if } g = 0 \\ \sum_{k=1}^g b_i^k & \text{if } g = j. \end{cases} \quad (1.3)$$

### **Individualized Price Auction Using Marginal Bid Price (MBP)**

In the MBP rule, each individual pays the same price for all units provided, and the price equals one's bid on the last unit that the group can collectively deliver. Let  $t_i$  denote the amount an individual has to pay contingent on the number of units being provided. Then we have:

$$t_i = \begin{cases} 0 & \text{if } g = 0 \\ j * b_i^j & \text{if } g = j. \end{cases} \quad (1.4)$$

### **Individualized Price Auction Using Marginal Pivotal Price (MPP)**

In the MPP rule, each individual pays the same price for each unit provided. However, different from MBP, the price is not directly determined by one's bid on the marginal unit. Instead, the price is calculated according to the pivotal mechanism, where individual  $i$  either pays nothing or the amount just needed to cover the cost. Let  $t_i$

denote the amount an individual has to pay contingent on the number of units being provided; we have:

$$t_i = \begin{cases} 0 & \text{if } g = 0 \\ j * \max(0, C - \sum_{k \neq i} b_k^j) & \text{if } g = j. \end{cases} \quad (1.5)$$

## 1.3 Properties of Different Mechanisms

### 1.3.1 Individual Profit

An individual's profit equals the total realized value minus the total cost paid, depending on the number of units that the group provides. Let  $\pi_i$  denote individual  $i$ 's profit, then

$$\pi_i = \begin{cases} 0 & \text{if } g = 0 \\ \sum_{k=1}^g v_i^k - t_i & \text{if } g = j. \end{cases} \quad (1.6)$$

Next we compare individual  $i$ 's profit for 1) PYB, the pay-your-bid auction; 2) MBP-AU, the ascending-unit marginal bid auction; 3) MBP-DU, the descending-unit marginal bid auction; 4) MPP-AU, the ascending-unit pivotal price auction; 5) MPP-DU, the descending-unit pivotal price auction. The MBP-AU (MBP-DU) is the individualized price auction using the marginal bid price combined with the ascending-unit (descending-unit) market clearing rule, while the MPP-AU (MPP-DU) is the individualized price auction using the marginal pivotal price combined with ascending-unit (descending-unit) market clearing rule. Profit functions are specified according to equation (1.6) by plugging in respective market clearing rules and pricing rules. Denote the  $\mathbf{b}_i = \{b_i^1 \dots b_i^J\}$  and  $\mathbf{b}_{-i} = \{b_1^1 \dots b_1^J \dots b_{i-1}^1, b_{i-1}^2 \dots b_{i-1}^J \dots b_{i+1}^1, b_{i+1}^2 \dots b_{i+1}^J \dots\}$ . Individual  $i$ 's profit is maximized when (assume  $g > 0$ )

$$\mathbf{b}_i^* \in \arg \max \pi_i = \arg \max \left( \sum_{k=1}^{g(\mathbf{b}_i, \mathbf{b}_{-i})} v_i^k - t_i(\mathbf{b}_i, \mathbf{b}_{-i}) \right). \quad (1.7)$$

Note that  $t_i(\cdot)$  is also a function of  $\mathbf{b}_{-i}$  when the marginal pivotal pricing is used; otherwise, individual  $i$ 's total private cost  $t_i(\cdot)$  is of a function only her own bids  $\mathbf{b}_i$ . Similarly, the total realized social surplus ( $RSS$ ), consumers' surplus ( $CS$ ) and producers' net revenue ( $PNR$ ) can be expressed as

$$RSS = \sum_{i=1}^N \sum_{k=1}^{g(\mathbf{b}_i, \mathbf{b}_{-i})} v_i^k - g(\mathbf{b}_i, \mathbf{b}_{-i})C, \quad (1.8)$$

$$CS = \sum_{i=1}^N \sum_{k=1}^{g(\mathbf{b}_i, \mathbf{b}_{-i})} (v_i^k - b_i^k), \quad (1.9)$$

and

$$PNR = \sum_{i=1}^N \sum_{k=1}^{g(\mathbf{b}_i, \mathbf{b}_{-i})} b_i^k - g(\mathbf{b}_i, \mathbf{b}_{-i})C. \quad (1.10)$$

### 1.3.2 Examples

We further explain the individualized price auction mechanisms using several numerical examples. Assume there are 3 contributors and 6 units available. Their values and bids on each unit are specified according to Table 1.1 . For example, from Table 1.1 , Contributor 1's value for the first unit is  $v_1^1 = 24$ , and Contributor 1's bid for the first unit is  $b_1^1 = 18$ . The unit cost is 30 and the same for every unit. Each contributor's value decreases as the unit number increases, which indicates a decreasing marginal benefit curve. Since the total value on the fourth unit is  $\sum_i v_i^4 = v_1^4 + v_2^4 + v_3^4 = 14 + 10 + 8 = 32 > 30$ , while the total value on the fifth unit



is  $\sum_i v_i^5 = v_1^5 + v_2^5 + v_3^5 = 8 + 4 + 6 = 18 < 30$ . Thus, it is socially optimal to provide 4 units.

According to the AU rule, only 3 units will be provided since the total of bids on each of the first three units is higher than the cost ( $B_1 = b_1^1 + b_2^1 + b_3^1 = 18 + 18 + 18 = 54 > 30$ ,  $B_2 = b_1^2 + b_2^2 + b_3^2 = 9 + 18 + 11 = 38 > 30$ ,  $B_3 = b_1^3 + b_2^3 + b_3^3 = 8 + 13 + 10 = 31 > 30$ ), while the total of bids on the 4th unit is smaller than its cost ( $B_4 = b_1^4 + b_2^4 + b_3^4 = 5 + 10 + 7 = 22 < 30$ ). Thus, the 4th unit is *not* provided, though providing the fourth unit could realize a higher social surplus.

Under the PYB, Contributors 1, 2 and 3 respectively obtain profit:

$$\begin{aligned}\pi_1 &= v_1^1 + v_1^2 + v_1^3 - b_1^1 - b_1^2 - b_1^3 = 23; \\ \pi_2 &= v_2^1 + v_2^2 + v_2^3 - b_2^1 - b_2^2 - b_2^3 = 4; \\ \pi_3 &= v_3^1 + v_3^2 + v_3^3 - b_3^1 - b_3^2 - b_3^3 = 2.\end{aligned}$$

Under the MBP-AU, the respective profit profile becomes:

$$\begin{aligned}\pi_1 &= v_1^1 + v_1^2 + v_1^3 - 3 * b_1^3 = 34; \\ \pi_2 &= v_2^1 + v_2^2 + v_2^3 - 3 * b_2^3 = 14; \\ \pi_3 &= v_3^1 + v_3^2 + v_3^3 - 3 * b_3^3 = 12.\end{aligned}$$

Under the MPP-AU, the profit profile is:

$$\begin{aligned}\pi_1 &= v_1^1 + v_1^2 + v_1^3 - 3 * \max(0, C - b_2^3 - b_3^3) = 36; \\ \pi_2 &= v_2^1 + v_2^2 + v_2^3 - 3 * \max(0, C - b_1^3 - b_3^3) = 17; \\ \pi_3 &= v_3^1 + v_3^2 + v_3^3 - 3 * \max(0, C - b_1^3 - b_2^3) = 15.\end{aligned}$$

Note that the DU auctions will still provide 3 units according to the value and

bid profile in Table 1.1 . We first evaluate the bids on the 6th unit; we find that  $B_6 = 4 < 30$ . We then evaluate the bids on the 5th unit and find  $B_5 = 21$ . We continue this process until we find  $B_3 = 31 > 30$ . Thus, 3 units will be provided using the DU auctions. The profit for MBP-DU(MPP-DU) is calculated the same way as MBP-AU(MPP-AU) when the number of units provided is the same.

### 1.3.3 Theoretical Remarks

#### Contribution Incentives at the Margin

In a multiple units public good environment, Nash equilibrium seldom leads to a socially efficient outcome. Even if we try to predict the outcome with stricter solution concepts (Bagnoli and Lipman, 1989), experimental results show that a refined Nash solution concept does not match outcomes very well (Bagnoli et al., 1992), possibly due to restrictive assumptions required for the equilibrium solutions. Practically, contributors often have limited information about others' value, which makes the characterization of the equilibrium strategies very complicated and analytically intractable in a multiple units public good context. While a complete equilibrium characterization would be interesting, it remains outside the scope of the current paper. As a result, we focus on the incentives for contribution at the margin (Marks and Croson, 1998). Specifically, we compare the differences in the marginal cost of providing an additional unit.

Note that individual  $i$ 's bid  $b_i^j$  on unit  $j$  enters the payoff function only if the  $j$ th unit can be provided. The marginal benefit of providing one additional unit,  $j$ , equals  $v_i^j$  for all mechanisms; however, the individual's marginal cost varies due to the difference in the pricing rules.

In PYB, the individual marginal cost of providing one additional unit (the cost difference in providing  $j$  units and providing  $j - 1$  units) is

$$MC_{PYB,i} = b_i^j,$$

since if the  $j$ th unit is provided, the total payment increases by  $b_i^j$ . In MBP-AU (or MBP-DU), individual  $i$ 's marginal cost of providing one additional unit is

$$MC_{MBP,i} = b_i^j + (j - 1)(b_i^j - b_i^{j-1}),$$

since if the  $j$ th unit is provided,  $i$ 's total payment increases by  $jb_i^j - (j - 1)b_i^{j-1}$  compared to when only  $j - 1$  units are provided.

The above marginal cost results suggest one potential advantage of the MBP approach is that it reduces the marginal cost of providing one additional unit compared to PYB when individuals lower their bids with a decreasing marginal value for more units. However, a \$1 reduction in  $b_i^j$  can reduce the marginal cost by more than a \$1 under MBP, compared to an exact \$1 reduction in the marginal cost under PYB. Such cost saving opportunities in MBP become more larger as  $j$  increases. For example, a \$1 reduction in  $b_i^j$  can reduce the marginal cost by  $\$1 \times 2 = \$2$  if  $j = 2$ , while the same \$1 reduction can lower the marginal cost by  $\$1 \times 4 = \$4$  for the marginal unit if  $j = 4$  under MBP. Therefore, we expect the advantage of lowering marginal cost using MBP gradually diminishes as the unit number  $j$  increases.

In MPP-AU (or MPP-DU), the marginal cost of providing one additional unit is

$$MC_{MPP,i} = \max(0, C - \sum_{k \neq i} b_k^j) + (j - 1) \left( \max(0, C - \sum_{k \neq i} b_k^j) - \max(0, C - \sum_{k \neq i} b_k^{j-1}) \right)$$

when the  $j$ th unit is provided. Depending on whether  $i$ 's bid is pivotal, the above equation can be written as:

$$MC_{MPP,i} = \begin{cases} 0 & \text{if } \sum_{k \neq i} b_k^{j-1} \geq C, \sum_{k \neq i} b_k^j \geq C; (a) \\ -(j-1)(C - \sum_{k \neq i} b_k^{j-1}) & \text{if } \sum_{k \neq i} b_k^{j-1} < C, \sum_{k \neq i} b_k^j \geq C; (b) \\ j(C - \sum_{k \neq i} b_k^j) & \text{if } \sum_{k \neq i} b_k^{j-1} \geq C, \sum_{k \neq i} b_k^j < C; (c) \\ C - \sum_{k \neq i} b_k^j + (j-1) \sum_{k \neq i} (b_k^{j-1} - b_k^j) & \text{if } \sum_{k \neq i} b_k^{j-1} < C, \sum_{k \neq i} b_k^j < C; (d) \end{cases} \quad (1.11)$$

The payoff function for MPP is complicated. Under the MPP rule, individual  $i$ 's cost of providing the unit  $j$  is not influenced by  $b_i^j$  directly. However,  $i$ 's bids on unit  $j-1$  and  $j$  will determine if  $i$ 's bid is pivotal to the provision success. Note that if individual  $i$ 's bid  $b_i^j$  is not pivotal (on unit  $j$  with  $\sum_{k \neq i} b_k^j \geq C$ ), the marginal cost of providing the unit  $j$  is zero or even negative (i.e., equation 1.11(a) and 1.11(b)). Realistically, as the group's offers gradually decrease with a smaller aggregated value, one's bid is more likely to be pivotal and individual  $i$ 's payoff is then determined by either equation 1.11(c) or 1.11(d). The marginal cost of providing unit  $j$  implied by 1.11(c) can be relatively high since the cost of providing  $j-1$  units is zero when the  $j$ th unit is provided. The marginal cost  $MC_{MPP,i}$  implied by 1.11(d) cannot be directly compared to  $MC_{PYB,i}$  or  $MC_{MBP,i}$  since  $C - \sum_{k \neq i} b_k^j < b_i^j$  but  $\sum_{k \neq i} b_k^{j-1} - \sum_{k \neq i} b_k^j > 0$  when the group contribution decreases with the unit number.

The above analyses compare the marginal cost of providing an additional unit. Compared to the PYB auctions, the MBP auctions offer a “rebate” on inframarginal unit  $k(k < j)$  determined by the difference between  $b_i^j$  and  $b_i^k$ ; the MPP auctions partially separate marginal cost from one's own bid on the marginal unit.<sup>3</sup> Besides the marginal contribution incentives, we are interested in which of the mechanism

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<sup>3</sup>In MPP auctions, individual  $i$ 's contribution can still influence one's profit as it will determine if the marginal (as well the inframarginal) contribution is pivotal to the provision success.

can yield a higher social efficiency in a multiple units public good environment. Thus we proceed to discuss the efficiency implications as well the surplus allocation.

### **Pareto Optimal Provision and Surplus Allocation**

We assume there is a market-maker or a social planner who is able to establish mechanisms to collect revenue and provide units of public good. We refer to the market-maker or the social planner as the public good “producer” in order to separate this agent from the contributors, who we call “consumers.” We are interested in the realized social surplus, as well as the split of the social surplus between consumers and producers (e.g., the market-maker or the social planner). We graphically present the social surplus between consumers and the producer, with a focus on different ways to allocate social surplus.

Figure 1.1 illustrates the realized social surplus, consumers’ surplus and producers’ net revenue. The realized social surplus equals the sum of values on each unit provided minus the total provision cost (i.e., the regions identified by  $ABEF$  for realized social surplus and the regions identified by  $ABQ'O$  for the total provision cost in Figure 1.1 ). The consumers’ surplus equals the sum of values on each unit provided minus the total bids paid (i.e., the blue regions represented in Figure 1.1 ). The producers’ net revenue equals the realized social surplus minus consumers’ surplus. The maximum social surplus equals the sums of values on all units for which aggregate value (marginal social benefit, MSB) exceeds provision cost minus the total provision cost if all those units would be delivered. Figure 1.1 (a), 1.1(b) and 1.1(c) respectively represent the pay-your-bids, individualized price auction using marginal bid price, and individualized price auction using marginal pivotal price rules.

In Figure 1.1 , the optimal quantity to be provided from a societal perspective is denoted by  $Q^*$ , which corresponds to the intersection of the marginal social benefit curve (MSB) and marginal social cost curve (MSC). The actual quantity provided by the group is denoted by  $Q'$ , which corresponds to the intersection of the aggregated contribution(offer) curve and MSC. The area identified by  $ACF$  (and bounded by the marginal social benefit curve) is the maximum social surplus, denoted by  $S_{ACF}$ ; the  $S_{ABEF}$  is the realized social surplus. Producers' net revenue equals the total expenses of the consumers (the red regions in Figure 1.1 ) minus the provision cost. Note that if we are using the pivotal pricing rule, the producer will either incur a deficit or just balance the budget. Therefore, when the maximum or realized social surplus is the same for the different rules,<sup>4</sup> the consumers' surplus (CS) is ranked according to:

$$CS_{MPP} \geq CS_{MBP} \geq CS_{PYB};$$

the producers' net revenue (PNR) is ranked by:

$$PNR_{PYB} \geq PNR_{MBP} \geq 0 \geq PNR_{MPP}.$$

### 1.3.4 The Change of Optimal Unit

In the multiple units public good experiment, the maximum number of units used by the researcher may serve as a signal on the potentially optimal unit, e.g., in our experiment, individuals are always asked to bid on 6 units. Thus, a framing effect

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<sup>4</sup>For the illustration in Figure 1.1 , we assume the MSC, MSB, the aggregate bidding curves are the same across different rules, which also implies the the number of units provided would be the same. Of course, the different rules may produce different aggregate bidding curves in the forthcoming experiments.

potentially exists and may contribute to the differences we observe among treatments (Kühberger et al., 1999; Sonnemans et al., 1998; Tversky and Kahneman, 1986). In our case, individuals might view an intermediate unit, say unit 3 or unit 4, as optimal and may give up efforts on the 5th or the 6th unit. To understand this framing effect, we include two additional experimental sessions where the provision of all units (6 units) are feasible and socially optimal, by increasing the induced value on each unit proportionally so that the last unit can always be provided with a positive net social surplus. These two additional treatments also provide a robustness check on the consistency of the experimental results when the socially optimal unit changes.

## 1.4 Experimental Procedure

We conducted eight experimental sessions in the CANR (College of Agriculture and Natural Resources) at the University of Connecticut (UConn). Subjects were recruited through the UConn Daily Digest (<http://dailydigest.uconn.edu>) where we placed advertisements asking for volunteer participants in economics experiments. The specific experimental tasks were not specified in the advertisements to avoid self-selection. Volunteers contacted researchers by email and received a confirmation email which only indicated it is an economics experiment involving multiple rounds of decision making. Our subject pool consists of mostly undergraduates and a few graduate students from various academic majors, who all expressed a willingness to participate in economic experiments by replying to the advertisement email. We checked the participants' names and email addresses, before confirming their attendance, to ensure each subject participated only once in this sequence of experiments.

We conducted experiments through networked computer terminals. Inter-participant communications during the experiment were prohibited and subjects could not observe each others' choices.

Subjects who appeared on-time were told that they had already earned a \$5 show-up fee before we proceeded to the instructions. The experiment's instructions were read aloud. Subjects were paid in cash once all treatments were finished. One experimental session usually lasted about one hour and twenty minutes with an average individual payoff around \$30. We controlled the total number of subjects to between 10 and 14 for each session with variation arising from individuals who failed to arrive at the start of each session.

Table 1.2 lists the treatments in the ten experimental sessions. Each treatment is replicated by at least four distinct groups of individuals. Sessions 1 to 6 compare the influence of different provision mechanisms; Sessions 7 to 8 change the socially optimal unit from 4 to 6, using PYB and MBP-AU mechanisms. Our experimental design responds to Charness et al. (2012)'s suggestions of combining within-subjects and between-subjects designs to utilize the advantages of both, with a counter-balancing experiment design to mitigate for order effects

In each session, subjects were assigned to one of two groups and were asked to make decisions in two treatments. Subjects were required to finish three quizzes that tested their understanding of the mechanism before making actual decisions in each treatment. The experiment moderator would then go through the quizzes with additional explanations of the rules. In each treatment, we separated all the subjects into two isolated groups. There were 10 decision periods in each treatment.

At the beginning of each decision period, individuals were told their induced values for six units of the public good. Induced values followed a uniform distribution on



the interval  $[20, 24]$  on Unit 1,  $[16, 20]$  on Unit 2,  $[12, 16]$  on Unit 3,  $[8, 12]$  on Unit 4,  $[4, 8]$  on Unit 5 and  $[0, 4]$  on Unit 6 in Sessions 1-6. Individual values in Sessions 7-8 were increased by 8 on average for each unit so that providing all six units would be the social optimum, e.g., the induced value range is  $[28, 32]$  on Unit 1 and  $[12, 16]$  on Unit 4.<sup>5</sup> All the induced values are rounded to the nearest tenth in the experiment. The range of induced values, the provision cost and the number of units are all public information. We set the provision cost for one unit equal to 8 times the number of all individuals in a group. Therefore, in Sessions 1-6, it was socially optimal to provide 4 units; in Session 7-8, it was socially optimal to provide 6 units. A total of 98 subjects participated in the experiment, producing 11,760 individual-unit level observations. Figure 1.2 shows a screenshot for the input screen. In actual experiments, individuals face a different induced value and the number of periods is also different than shown in Figure 1.2 .

## 1.5 Experiment Result and Discussion

In this section, we present experiment results, focusing on the differences between the individualized price auction and the pay-your-bids auction. We also discuss the results when the socially optimal provision unit changes from 4 to 6.

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<sup>5</sup>When providing four units is optimal, the ratios of per unit provision cost over the per unit expected total benefits (the sum of induced value for a group on one unit) are (from Unit 1 to 6): 36.36%, 44.44%, 57.14%, 80%, 133% and 400%; according to the range on value on each unit, the ratios of per unit provision cost over the per unit realized total benefits can vary from 33.33% to 40.00%, 40.00% to 50.00%, 50.00% to 66.67%, 66.67% to 100%, 100% to 200% and above 200%, respectively for Unit 1 to Unit 6. When providing six units is optimal, the ratios of per unit provision cost over the per unit expected total benefits (from Unit 1 to 6) are: 26.67%, 30.77%, 36.36%, 44.44%, 57.14% and 80%.

### 1.5.1 Group Contribution Results

**Result 1.** Subjects rarely reach the Pareto optimal provision level in all mechanisms. The MPP-AU has the highest rate, while the PYB has the lowest rate in providing three or more units, when providing 4 units is optimal.

Table 1.3 reports the provision frequency of each unit for different treatments. Table 1.4 reports the provision frequency in an accumulative manner: each column summarizes the provision frequency where at least a certain number of units is provided. From Table 1.3 and 4, we find that when providing 4 units is optimal, subjects rarely reach the efficient provision level, except several occasions with the marginal pivotal pricing rules. Subjects never provide more than 4 units in any cases. When providing 6 units is optimal, subjects provided 5 units on several occasions, but they never reached the efficient provision level.<sup>6</sup>

We find that in the ascending-unit auctions, the pivotal pricing rule performs best in terms of providing 3 or more units (frequency of providing 3 or more units: 45%) while the marginal bid pricing rule has the lowest complete provision failure (frequency of providing at least one unit: 96.25%). The difference between pivotal pricing and marginal bids provision is not obvious in the descending auctions. Compared to the PYB mechanism, all the individualized price mechanisms perform better in providing 3 or more units, among which the MPP-AU generates the largest increase is 25% compared to PYB. Due to the limited sample size, we implemented the Fisher's exact test for the null hypothesis that the probabilities of providing 3 or more units

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<sup>6</sup>Note that the total benefits on the 4th (or 6th when providing all units is social optimal) unit are only about 25% higher than the cost on average. This provision cost/benefit ratio is considered relatively high and successful provision can be difficult even for a single unit (Cadsby and Maynes, 1999).

are the same under PYB and MPP-AU.<sup>7</sup> Our results reject the null hypothesis at a 5% significant level ( $p = 0.043$ ). To confirm the robustness of our results, we conduct additional regressions using a probit model<sup>8</sup> where the dependent variable  $p_{gt}^j$  is a binary outcome which equals 1 if the group  $g$  in period  $t$  provides at least  $j$  unit(s). We also control for the time trend and session fixed effects in the model. The estimation results are shown in Table 1.5 . We find that the treatment MBP-AU significantly increases the provision frequency of providing two units or more compared to PYB while confirming the result that MPP-AU increases the provision frequency of providing three units or more compared to PYB.

**Result 2.** The DU mechanisms tend to produce a larger probability of complete non-provision compared to AU counterparts.

In terms of complete provision failures, we find that the two descending-unit auctions performs notably worse than their ascending-unit counterparts, especially with the marginal bid pricing rule (Fisher exact test, difference in the provision frequency of 0 units:  $p < 0.001$ ). The differences between AU and DU of providing 0 units are not significant for the marginal pivotal pricing rule at the conventional significance level (Fisher exact test, difference in the provision frequency of 0 units:  $p = 0.77$ ). This result suggests that the market clearing rule does make a difference in influencing the overall provision success. Even though the DU auction requires less stringent conditions to achieve a higher provision rate (e.g., the DU auctions only require the total contribution on the fourth unit to be higher than the cost to provide four units while the AU auctions require the total offer of each unit from unit 1 to unit 4 to

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<sup>7</sup>See Imbens and Wooldridge (2009) for a detailed discussion on the advantages of using Fisher's exact test with a limited sample size.

<sup>8</sup>A logistic regression yields similar results.

be higher than the cost), our experimental results suggest the DU auctions perform worse due to a higher possibility of complete provision failures.

**Result 3.** The increase of marginal value on each unit significantly boosts the provision success.

When it is optimal to provide 6 units, we find that the provision frequency of providing three or more units is much higher compared to the situation where providing 4 units are optimal (provision frequency of providing 3 or more units: PYB (20%) compared with PYB-6 (60%),  $p < 0.001$ ; MBP-AU (30%) compared with MBP-AU-6 (60%),  $p < 0.001$ , Fisher exact test.). However, since the value distribution is the same on the inframarginal unit (the 3rd unit when providing 4 unit is optimal, and the 5th unit when providing 6 units is optimal), we find there is a decrease in provision success on the inframarginal unit when providing 6 units is optimal, though such a decrease is not significant in PYB (provision frequency of providing the inframarginal unit: PYB (20%) compared to PYB-6 (10%),  $p = 0.512$ ; MBP-AU (30%) compared with MBP-AU-6 (5%),  $p = 0.018$ ).

**Result 4.** When providing 4 units is optimal, the PYB realizes the lowest social surplus and consumer surplus in the last five periods; When providing 6 units is optimal, MBP-AU-6 realizes a higher social surplus and consumer's surplus compared to PYB-6.

In Table 1.5 , we summarize the maximum social surplus, realized social surplus and producers' net revenue by treatment and we present results separately for all 10 periods, the first 5 periods and the last 5 periods. Since the group size varies across sessions, the numbers are scaled to a group-size of five: for example, if realized social

surplus is 120 for a group size of six, then the adjusted realized social surplus is  $120 \times 5/6 = 100$ . The parenthesized percentages in the realized social surplus column are the efficiency levels, which equal the realized social surplus divided by the maximum social surplus; the parenthesized percentages in the consumers' surplus column are the share of consumers' surplus, which equals the consumers' surplus divided by the realized social surplus; the parenthesized percentages in the producers' net revenue column are the share of producers' net revenue, which equals the producers' net revenue divided by the realized social surplus.

From Table 1.5, we observe that the overall efficiency level ranges from 58% to 72% (when providing 4 units are optimal), with the MBP-AU being the highest and MBP-DU being the lowest in 10 periods. Comparing the efficiency result from the first 5 periods with the results from the last 5 periods, we find that the PYB sees the largest decrease in the overall efficiency (in terms of percentage, social surplus decreases from 67% in the first 5 periods to 53% in the last 5 periods), while MPP-DU sees a moderate increase in the efficiency level (increasing from 61% in the first 5 periods to 67% in the last 5 periods); other mechanisms all experienced a slight decrease in the overall efficiency level. Generally, the DU auctions either experienced a small decrease (MBP-DU,  $-2\%$ ) or a small increase (MPP-DU  $6\%$ ) from the first 5 to the last 5 periods. In contrast, the magnitude of efficiency decrease is higher in the AU mechanisms (PYB:  $-14\%$ ; MBP-AU:  $-6\%$ ; MPP-AU:  $-8\%$ ). When providing 6 units is optimal, we find the the PYB-6 also has a slightly larger decrease in the efficiency level compared to MBP-AU-6 from the first 5 periods to the last 5 periods (PYB,  $-16\%$ ; MBP-AU,  $-12\%$ ); again, the overall efficiency level is higher for MBP-AU-6 compared to PYB-6.

In terms of the allocation of realized social surplus, Figure 1.3 presents the differ-

ence of surplus allocation among different provision mechanisms. Figure 1.4 presents the difference of surplus allocation for PYB and MBP-AU after the optimal provision unit is changed from 4 to 6. In the last five periods, the realized social surplus is ranked by

$$MBP-AU > MPP-DU > MPP-AU > MBP-DU > PYB;$$

the consumers' surplus is ranked by

$$MPP-DU > MPP-AU > MBP-AU > MBP-DU > PYB;$$

the producers' net revenue is ranked by

$$MBP-AU > MBP-DU > PYB > 0 > MPP-AU > MPP-DU.$$

The producers' net revenue is negative in MPP-AU and MPP-DU because the pivotal pricing will almost surely result a deficit for the producer and the transfer of surplus to consumers makes the consumer's surplus unsurprisingly exceed 100%. We also find that when providing 6 units is optimal, MBP-AU-6 achieves a higher social surplus and consumer's surplus, but a lower producers' net revenue compared to PYB-6. Two sample t-tests are conducted to test whether the above differences are significant. Detailed test results are presented below each figure. Note that the MBP-AU achieves almost a one third (31%) net increase in the realized social surplus compared to PYB with 4 units being optimal while such an increase is about 12% with 6 units being optimal. One may think that 12% is a notable reduction compared to a 31% increase; however, this result is merely an artifact of the huge increase in total available social surplus when the optimally provided unit changes from 4 to 6. The average increases are very close in magnitude in these two situations. The increases in average social surplus are 26 when providing 4 units is optimal and 24.5 when providing 6 units is optimal, which equal to 52% and 49% of the surplus available from the social marginal unit, respectively.

**Result 5.** Compared to a counterfactual scenario where "subjects" are assumed to contribute randomly between 0 and their induced values, in the lab experiments, PYB and AU auctions realize a higher percentage of the potential social surplus, DU auctions realize a lower percentage of the potential social surplus compared to the counterfactual scenarios. PYB and MBP rules realize a higher share of consumer surplus while MPP rules realize a lower share of consumer surplus compared to the counterfactual scenarios.

The purpose of the counterfactual simulation is to construct a benchmark where human contributors are replaced with a computer program wherein each "subject" contributes randomly between zero and their induced values. The allocative efficiencies generated from the counterfactual benchmarks are then compared to the experiment outcomes (Gode and Sunder, 1993, 1997). The simulation results are summarized in the squared brackets in the Table 1.5 . We find that PYB and two AU auctions perform better than the counterfactual benchmarks where subjects just contribute randomly with the induced value constraint. The increase of realized social surplus ranges from 7% (PYB) to 19% (MBP-AU) with 4 units optimal and from 0% (PYB-6) to 5% (MBP-AU) with 6 units optimal. Interestingly, the two DU mechanisms perform worse than the counterfactual benchmark. The loss in efficiency ranges from  $-5\%$  (MPP-DU) to  $-9\%$  (MBP-DU). We also find that subjects are able to collectively acquire a larger share of realized social surplus under PYB and MBP mechanisms through strategic interactions, while subjects acquire a significantly lower share of realized social surplus under the MPP mechanisms compared to the counterfactual benchmarks.

### 1.5.2 Individual Contribution Results

**Result 6.** The average marginal bid is significantly higher in MBP-AU compared to PYB on the the first and second unit; such differences become insignificant as the unit number increases.

Table 1.7 and Table 1.8 report the average marginal bid on each unit across different treatments for the first 5 and the last 5 periods, respectively. Figure 1.3 presents the change of average marginal bid of MBP-AU compared to PYB from the first 5 periods to the last 5 periods separately on unit 1 to unit 6. From Figure 1.3, we find that in the first 5 periods, the average marginal contribution is significantly higher in the MBP-AU(or the MBP-AU-6) compared to PYB (or the PYB-6) on the first and the second unit; such differences are mostly statistically significant according to the Mann-Whitney  $U$  test (Unit 1: 4 unit optimal,  $p = 0.082$ ,  $z = 1.736$ , 6 unit optimal,  $p < 0.001$ ,  $z = 5.284$ ; unit 2: 4 unit optimal,  $p = 0.715$ ,  $z = 0.364$ , 6 unit optimal,  $p = 0.0157$ ,  $z = 2.417$ ). In the last 5 periods, the difference between PYB and MBP-AU decreases, however, such difference is still statistically significant. (Mann-Whitney  $U$  test Unit 1: 4 unit optimal,  $p < 0.001$ ,  $z = 4.182$ , 6 unit optimal,  $p < 0.001$ ,  $z = 6.351$ ; unit 2: 4 unit optimal,  $p = 0.048$ ,  $z = 1.970$ , 6 unit optimal,  $p < 0.001$ ,  $z = 4.318$ .) The differences between MBP-AU(MBP-AU-6) and PYB (PYB-6) are not significant on the remaining units except on the 6th unit, MBP-AU is significant higher than PYB, despite their small difference in absolute value. Our results suggest that the main advantage of MBP-AU is to reduce very inefficient provision outcomes (e.g., providing 0 units or only 1 unit) by attracting more contributions on the first two units compared to PYB.

**Result 7.** The DU auctions have a larger proportion of near-zero bids on the first



two units.

We report the number of near-zero bids, which is defined as bids smaller than or equal to 1 experimental dollar, in Table 1.7 . We find that in the DU auctions, there is a larger proportion of near-zero bids compared to the AU counterparts on the first two units (Fisher exact test: Unit 1, MBP rule,  $p < 0.001$ , MPP rule,  $p < 0.001$ ; Unit 2, MBP rule,  $p < 0.0038$ , MPP rule,  $p = 0.6301$ ). The DU mechanisms are not as effective as AU mechanisms in raising revenue on the first several units due to near-zero contributions, which leads to the overall differences in the realized social surplus. Contributions lower than or equal to \$1 suggest either the non-participation decisions or (strategic) free-riding behaviors, which prevent the DU auctions from achieving a high provision success by losing contributions on the first two units in which the group holds relative high values.

**Result 8.** Individuals strategically lower the contribution on the inframarginal units to lower the marginal cost on the provided unit under the MPP rules.

We find that under the MBP rules, there is a high percentage of near-zero contributions on the unit 2, and a sudden decrease of near-zero contributions on unit 3 (Table 1.7 , Table 1.8 ). In the first 5 periods, the percentage near-zero contributions decreases from 15.45% to 0.48% for MPP-AU and decreases from 22.41% to 7.69% for MPP-DU. In the last 5 periods, the percentage of near-zero contributions decrease from 22.73% to 4.55% for MPP-AU and decrease from 17.69% to 4.62% for MPP-DU. Such decreasing trends are not observed for the MBP counterparts where the *change* of percentage for the near-zero contributions are 2.50%, 2.31% respectively in the first 5 periods and 2.08%, -0.77% respectively in the last 5 periods. This result is consistent with the evidence that the average marginal bids on unit 2 and unit 3 are

almost the same. Differences in group composition cannot explain the observed pattern: according to our experimental design (Table 1.2 ), the same groups of subjects went through both MB-AU (or MB-DU) and MP-AU (or MP-DU). Our counterbalance design also mitigates the concerns for order effects. This result suggests subjects strategically respond to the pivotal pricing rule when applied to a multiple units context. Recall in equation(1.11), the marginal cost of providing an additional unit  $j$  depends on whether one's bid is pivotal or not on unit  $j - 1$  and unit  $j$ . Table 1.9 summarizes the counts of individual contributions pivotal on unit  $j - 1$  and unit  $j$  if  $j$  units were provided. From Table 1.9 , we observe that if three units were provided, one's marginal cost of providing the third unit is likely to be determined by equation 1.11(d). Thus, when the group contribution on the second unit ( $\sum b_i^2$ ) is similar to the group contribution on the third unit ( $\sum b_i^3$ ), each individual is more likely to face a smaller marginal cost of providing the third unit. In this sense, we infer individuals act collectively to reduce the group contribution on the second unit (but still higher than provision cost) such that each individual has an incentive to contribute more to support the third unit. Otherwise, if individual bids are relative high on the second unit and no one is pivotal if two units are provided, the individual provision cost is zero for providing two units. However, the cost will increase substantially for some individuals when three units are provided.

To assess the treatment effect quantitatively, we run several regression models comparing different provision mechanisms with the baseline PYB. The regression results enable us to uncover several interesting results hidden by summary statistics and nonparametric tests. We use a random effects model to account for individual-specific effects.

**Result 9.** Compared to the PYB, MBP-AU encourages a higher value revelation ratio on the first three units but the bids decrease faster from unit 1 to unit 4 compared to the decreasing trend in PYB.

From the marginal contribution incentives analysis, we notice that one's contribution decision on a unit can be dependent on the decision for the previous unit. For example, the bid amount on the first unit may influence the contribution incentive on the second unit. Thus, we include a unit-lagged term in the regression model, except for the first unit. For the first unit, the regression model is:

$$b_{it}^1 = \beta_1 v_i^1 + \sum_k \beta_{2k} v_i^1 * IPA_k + \beta_5 Period + \beta_6 Cons + u_i + \epsilon_{it}; \quad (1.12)$$

for the other units, the regression model is

$$b_{it}^j = \beta_1 v_i^j + \sum_k \beta_{2k} v_i^j * IPA_k + \beta_3 b_{it}^{j-1} + \sum_k \beta_{4k} b_{it}^{j-1} * IPA_k + \beta_5 Period + \beta_6 Cons + u_i + \epsilon_{it}; \quad (1.13)$$

where the dependent variable  $b_{it}^j$  is individual  $i$ 's bid on unit  $j$  in period  $t$ . The  $v_i^j$  represents individual  $i$ 's induced value on unit  $j$ , while  $IPA_k$  is a dummy variable that differentiates each individualized price mechanism with PYB treated as the baseline; *Period* captures the time trend. The term  $u_i$  is the individual-specific random effect across different periods; the term  $\epsilon_{it}$  is individual-period specific error. Table 1.10 reports the regression results. The odd numbered models include individual's induced value, and a unit-lagged bid ( $b^{j-1}$ ), while the even numbered models include additional terms of these two variables interacted with different IPA mechanisms. Compared to the PYB baseline, we find that the MBP-AU encourages a higher value revelation ratio, which implies a higher contribution on the first three units. The MBP-DU

and MPP-DU only significantly increases contribution on the inframarginal or the marginal unit (unit 3 for DU-MPP, and unit 4 for DU-MBP); the AU-MPP increases the contribution on the third unit, however it decreases contributions on the second and fourth unit.

Negative significant coefficients are observed for the unit-lagged interaction terms on the first 4 units, while on the last two units, the interaction terms are generally positive, some of them are significant. Since the main effect of the unit-lagged term is positive, it indicates that compared to the PYB, in the IPA mechanisms, the bids decrease *faster* from unit 1 to unit 4. One notable result from the regression table is the low  $R^2$  observed for the first unit, where the induced value ranges from  $[20, 24]$  while the provision cost is constant at  $8N$  with  $N$  representing the group size. The equilibrium strategy in this setting for a single unit threshold public good is the equal cost sharing strategy (Borgers et al., 2015). Each individual will share the provision cost and contribute equally. Though our experimental setting is very different from a single unit threshold public good provision, this insight may explain why the induced value is a poor predictor on contribution of the first or the second unit. We find the induced value coefficient  $\beta_1$  only becomes positively significant starting from the third unit.

## 1.6 Conclusion

Our experiments explore several novel provision approaches to provide multiple units of public good in discrete increments. Our results suggest significant differences between these provision mechanisms in terms of provision success and value revelation.

Most strikingly, we find significant improvement in social efficiency for individualized price auction approaches. Our research brings new provision mechanisms into the multiple units public good provision and we expect more studies on the multiple unit public good provision problem, since a successful mechanism can be crucial in raising private donations to establish a functional (e.g., environmental) market that can provide public goods (e.g., ecosystem services) in a decentralized way. We also expect crowdfunding industry will benefit from innovative auction mechanisms to support various projects through public contributions, such as using the IPA rule to support a larger project with a higher success probability.

The individualized price auctions correspond to Lindahl (1919) framework where each individual shares the cost that is determined by the intersection of marginal cost and marginal social benefit and their private value being included in the social benefit. We find that such approaches can improve efficiency relative to a straightforward pay-your-bid approach in a multiple units public good context. We experimentally explore several variants of the Lindahl-inspired auction approaches. Such auction approaches may help increase private contributions to support multiple units or levels of a public project, and help individuals reach out to the optimal provision with a lower average unit price.

In the PYB mechanism, it is obvious individuals do not have the incentive to reveal their full values; their contributions would influence their actual cost. According to Bagnoli and Lipman (1989) and Bagnoli et al. (1992), any contributions adding up to the cost with no individual's contribution exceeding his valuation is an equilibrium, while in a successively undominated strictly perfect equilibrium (SUSPE), the equilibrium "core" will be implemented. However, as pointed out in Bagnoli et al. (1992) , *"...The problem of obtaining the efficient outcome is much more diffi-*

*cult and implementing the core requires a very strong refinement notion...the use of such a strong refinement immediately raises the questions of its behavioral realism.”*

Thus, we expect the experimental outcome of PYB mechanism to be suboptimal. Though our proposed IPA mechanisms still fall short of reaching 100% efficiency, experimental results show substantial efficiency gains are achieved through various IPA mechanisms.

Note that different from Bagnoli et al. (1992), where contributions are solicited sequentially,<sup>9</sup> we solicit multiple contributions from an individual at the same time. Our approach enables us to obtain individual contribution behaviors for the units that are outside the optimal provision set. Future research in this area can be fruitful. Theoretically, new mechanisms are required to address the problem of the inefficient equilibrium in multiple units of public goods provision. Equally important, empirical work is needed on how to encourage both participation and contribution in real fund raising activities using a transparent and easily understandable mechanism to realize most of the potential social surplus.

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<sup>9</sup> Bagnoli et al. (1992) start soliciting the bids on the first unit only, and they calculate the outcome. Depending on the provision outcome of the first unit, they will decide whether or not to continue asking and evaluating bids on the second unit, and so on. In our approach, we ask individuals to make a contribution on each unit at the same time, although the auctioneer still evaluate aggregated bids sequentially.

TABLE 1.1: Numerical Example

Unit	Contributor 1	Contributor 2	Contributor 3	Cost
1	$v_1^1 = 24, b_1^1 = 18$	$v_2^1 = 20, b_2^1 = 18$	$v_3^1 = 19, b_3^1 = 18$	30
2	$v_1^2 = 18, b_1^2 = 9$	$v_2^2 = 19, b_2^2 = 18$	$v_3^2 = 13, b_3^2 = 11$	30
3	$v_1^3 = 16, b_1^3 = 8$	$v_2^3 = 14, b_2^3 = 13$	$v_3^3 = 10, b_3^3 = 10$	30
4	$v_1^4 = 14, b_1^4 = 5$	$v_2^4 = 10, b_2^4 = 10$	$v_3^4 = 8, b_3^4 = 7$	30
5	$v_1^5 = 8, b_1^5 = 4$	$v_2^5 = 4, b_2^5 = 13$	$v_3^5 = 6, b_3^5 = 4$	30
6	$v_1^6 = 4, b_1^6 = 2$	$v_2^6 = 3, b_2^6 = 0$	$v_3^6 = 3, b_3^6 = 2$	30

Note: In the example, there are six units available in total and three contributors. The  $v_i^j$  denotes individuals  $i$ 's induced value on unit  $j$ ; the  $b_i^j$  denote individuals  $i$ 's bid on unit  $j$ . There are three contributors and the cost is 30 for each unit.

TABLE 1.2: Experiment Sequence

Session	Treatment 1	Treatment 2	Group Size ×No. of Groups	Total Unit Available	Socially Optimal Unit	Unit Cost
1	PYB	MBP-AU	7×2	6	4	56
2	MBP-AU	PYB	6×2	6	4	48
3	MBP-AU	MPP-AU	5×2	6	4	40
4	MPP-AU	MBP-AU	6×2	6	4	48
5	MBP-DU	MPP-DU	7×2	6	4	56
6	MPP-DU	MBP-DU	6×2	6	4	48
7	PYB-6	MBP-AU-6	6×2	6	6	48
8	MBP-AU-6	PYB-6	6×2	6	6	48

Note: Sessions 1 to 6 test different provision mechanisms, with two additional sessions focused on the effect from changing the optimal units. The group size is from 5 to 7. In each session, subjects were randomly assigned to one of two groups and were asked to make decisions in two treatments. A participant's group membership remained unchanged for one treatment. There were 10 decision periods in each treatment.



TABLE 1.3: Summarize Statistics at the Group Level: Percentage of Decision Periods with the Number of Units (from 0 units to 6 units) Provided

Provided	0 Units	1 Unit	2 Unit	3 Unit	4 Unit	5 Unit	6 Unit	Obs.(each treat.)
<i>Baseline</i>								
PYB	10%	42.5%	27.5%	20%	0%	0%	0%	40
<i>Ascending-Unit Auction</i>								
MBP-AU	3.75%	21.25%	45%	30%	0%	0%	0%	80
MPP-AU	15%	20%	17.5%	45%	2.5%	0%	0%	40
<i>Descending-Unit Auction</i>								
MBP-DU	25%	20%	27.5%	27.5%	0%	0%	0%	40
MPP-DU	20%	15%	32.5%	27.5%	5%	0%	0%	40
<i>6 Units are Optimal</i>								
PYB-6	5%	20%	15%	22.5%	27.5%	10%	0%	40
MBP-AU-6	5%	10%	12.5%	32.5%	35%	5%	0%	40

TABLE 1.4: Summarize Statistics at the Group Level: Percentage of Decision Periods with At Least the Number of Units  
(from 0 units to 6 units) Provided

Provided	$\geq 1$ Unit	$\geq 2$ Units	$\geq 3$ Units	$\geq 4$ Units	$\geq 5$ Units	$\geq 6$ Units	Obs.(each treat.)
<i>Baseline</i>							
PYB	90%	47.5%	20%	0%	0%	0%	40
<i>Ascending-Unit Auction</i>							
MBP-AU	96.25%	75%	30%	0%	0%	0%	80
MPP-AU	85%	65%	45%	2.5%	0%	0%	40
<i>Descending-Unit Auction</i>							
MBP-DU	75%	55%	27.5%	0%	0%	0%	40
MPP-DU	80%	65%	32.5%	5%	0%	0%	40
<i>6 Units are Optimal</i>							
PYB-6	95%	75%	60%	37.5%	10%	0%	40
MBP-AU-6	95%	85%	72.5%	40%	5%	0%	40

TABLE 1.5: The Influence of Treatment on Provision Probability

	(1) ≥ 1 Unit	(2) ≥ 2 Units	(3) ≥ 3 Units
Treatment			
MBP-AU	0.516 (0.380)	0.753** (0.252)	0.324 (0.271)
MPP-AU	-0.249 (0.367)	0.461 (0.288)	0.784** (0.303)
MBP-DU	-0.610 (0.350)	0.189 (0.282)	0.245 (0.311)
MPP-DU	-0.448 (0.356)	0.456 (0.286)	0.382 (0.308)
Period	-0.0349 (0.0376)	-0.0530 (0.0296)	-0.0304 (0.0299)
Cons.	1.304*** (0.363)	0.0758 (0.269)	-0.834** (0.287)
Session fixed effects	YES	YES	YES
$N$	240	240	240

Standard errors in parentheses

\*  $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$

TABLE 1.6: Realized Social Surplus, Consumers' Surplus and Producers' Net Revenue

Period	Maximum Social Surplus	Realized Social Surplus	Consumers' Surplus	Producers' Net Revenue
<i>Baseline</i>				
PYB <i>Total</i>	158	95 (60%) [53%]	78.5 (83%) [76%]	16.5 (17%) [24%]
<i>First 5</i>	158	106 (67%)	82 (77%)	24 (23%)
<i>Last 5</i>	158	84 (53%)	75 (89%)	9 (11%)
<i>Ascending-Unit Auction</i>				
MBP-AU <i>Total</i>	159	114.5 (72%) [53%]	100 (87%) [81%]	15 (13%) [19%]
<i>First 5</i>	159	119 (75%)	104 (87%)	15 (13%)
<i>Last 5</i>	159	110 (69%)	96 (87%)	14.5 (13%)
MPP-AU <i>Total</i>	159	106.5 (67%) [53%]	135 (127%) [168%]	-28.5 (-27%) [-68%]
<i>First 5</i>	159	112.5 (71%)	137 (122%)	-24.5 (-22%)
<i>Last 5</i>	159	100.5 (63%)	133.5 (133%)	-32.5 (-33%)
<i>Descending-Unit Auction</i>				
MBP-DU <i>Total</i>	158	92 (58%) [67%]	80 (87%) [83%]	12.5 (13%) [17%]
<i>First 5</i>	158	94 (59%)	80 (86%)	13.5 (14%)
<i>Last 5</i>	158	90.5 (57%)	79 (87%)	11.5 (13%)
MPP-DU <i>Total</i>	158	101 (64%) [67%]	136.5 (135%) [170%]	-35.5 (-35%) [-70%]
<i>First 5</i>	158	96.5 (61%)	130.5 (135%)	-34 (-35%)
<i>Last 5</i>	158	105.5 (67%)	142 (135%)	-36.5 (-35%)
<i>6 Units are Optimal</i>				
PYB-6 <i>Total</i>	322	237.5 (74%) [74%]	207.5 (87%) [71%]	30.5 (13%) [29%]
<i>First 5</i>	322	262.5 (82%)	226 (86%)	36.5 (14%)
<i>Last 5</i>	322	212.5 (66%)	188.5 (89%)	24 (11%)
MBP-AU <i>Total</i>	325	257 (79%) [74%]	237 (92%) [83%]	19.5 (8%) [17%]
<i>First 5</i>	325	277 (85%)	252.5 (91%)	24.5 (9%)
<i>Last 5</i>	325	237 (73%)	222 (94%)	15 (6%)

Note: This table summarizes the maximum social surplus, realized social surplus, consumers' surplus and producers' net revenue for different provision mechanism. We also include the combine results and separated results for the first 5 and the last 5 experiment periods. The percentage numbers in parentheses in the realized social surplus column represent the efficiency level, which is calculated from the realized social surplus divided by the maximum social surplus. The percentage numbers in parentheses in the consumers' surplus (producers' net revenue) column represent the allocation of the realized social surplus, which is calculated from the consumers' surplus (producers' net revenue) divided by the maximum social surplus. Percentages in square brackets represent the simulation results for realized social surplus, consumers' surplus and producers' net revenue assuming each subject randomly contribute an amount between 0 up to her induced value under different mechanisms.

TABLE 1.7: Summarize Statistics at the Individual Level: Average Marginal Contribution First 5 Periods

Treatment	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Obs.(each unit.)
<i>Baseline</i>							
PYB	10.98(5.91)	8.94(4.77)	6.97(3.85)	4.74(2.85)	3.06(1.99)	0.87(0.91)	130
<i>No. of Obs.(j=1)</i>	0(0%)	0(0%)	4(3.08%)	14(10.77%)	17(13.08%)	78(60%)	
<i>Ascending-Unit Auction</i>							
MBP-AU	13.09(6.46)	9.87(5.75)	7.22(4.07)	4.89( 2.84)	3.26(2.31)	1.13(1.37)	240
<i>No. of Obs.(j=1)</i>	2(0.83%)	2(0.83%)	8(3.33%)	17(7.08%)	30(12.5%)	122(50.83%)	
MPP-AU	10.86(5.87)	7.64(5.42)	7.26(3.65)	4.75(2.98)	3.16(2.45)	1.21(1.99)	110
<i>No. of Obs.(j=1)</i>	2(1.81%)	17(15.45%)	1(0.48%)	13(11.82%)	21(19.09%)	57(51.82%)	
<i>Descending-Unit Auction</i>							
MBP-DU	10.73(7.17)	9.07(5.60)	7.26(4.51)	5.00(2.93)	3.20(2.27)	1.28(1.77)	130
<i>No. of Obs.(j=1)</i>	14(10.77%)	9(6.92%)	12(9.23%)	13(10%)	23(17.69%)	66(50.77%)	
MPP-DU	9.68(6.90)	7.60(6.15)	7.85(5.30)	4.92(3.87)	3.62(3.49)	1.21(2.51)	130
<i>No. of Obs.(j=1)</i>	14(10.77%)	29(22.31%)	10(7.69%)	10(7.69%)	15(11.54%)	76(58.46%)	
<i>6 Units are Optimal</i>							
PYB-6	11.00(7.98)	10.29(6.10)	8.95(5.30)	7.38(4.95)	5.71(4.46)	3.87(3.02)	120
<i>No. of Obs.(j=1)</i>	19(15.83%)	11(9.17%)	12(10%)	21(17.5%)	27(22.5%)	29(24.12%)	
MBP-AU-6	17.09(7.53)	13.13(7.17)	10.61(6.20)	7.76(5.76)	5.36(4.48)	3.94(3.90)	120
<i>No. of Obs.(j=1)</i>	1(0.83%)	5(4.17%)	8(6.77%)	22(18.33%)	26(21.67%)	31(25.83%)	

Note: This table summarize average marginal contribution on each unit for different provision mechanisms, in the first 5 periods. Standard deviations are included in the parentheses in rows starting with auction mechanism, e.g., "PYP". We also summarize the frequency of low contributions (individual contribution smaller than 1 experimental dollar); the percentages of the low contributions are included in the parentheses in rows starting with "No. of Obs.(j=1)".

TABLE 1.8: Summarize Statistics at the Individual Level: Average Marginal Contribution Last 5 Periods

Treatment	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Obs.(each unit.)
<i>Baseline</i>							
PYB	9.30(4.60)	8.02(3.73)	6.88(3.50)	4.93(2.83)	3.33(1.89)	0.99(1.07)	130
No. of Obs.( $j=1$ )	0(0%)	0(0%)	2(1.54%)	11(8.46%)	13(10%)	73(56.15%)	
<i>Ascending-Unit Auction</i>							
MBP-AU	12.04(10.04)	8.94(6.16)	6.88(4.35)	4.83(3.21)	3.31(2.61)	1.26(1.42)	240
No. of Obs.( $j=1$ )	4(1.67%)	9(3.75%)	14(5.83%)	30(12.5%)	41(17.08%)	111(46.25%)	
MPP-AU	11.44(6.14)	7.73(5.99)	7.37(4.45)	4.99(3.45)	3.40(2.91)	1.49(2.64)	110
No. of Obs.( $j=1$ )	4(3.64%)	25(22.73%)	5(4.55%)	10(9.09%)	18(16.36%)	51(46.35%)	
<i>Descending-Unit Auction</i>							
MBP-DU	10.33(7.05)	8.72(6.01)	6.85(4.99)	5.12(3.81)	3.42(3.06)	1.53(2.43)	130
No. of Obs.( $j=1$ )	16(12.31%)	16(12.31%)	15(11.54%)	12(9.23%)	19(14.62%)	64(49.25%)	
MPP-DU	10.44(7.30)	7.74(5.97)	7.34(4.66)	4.91(3.57)	3.52(3.31)	1.63(3.54)	130
No. of Obs.( $j=1$ )	22(16.92%)	23(17.69%)	6(4.62%)	8(6.15%)	14(18.46%)	74(56.92%)	
<i>6 Units are Optimal</i>							
PYB-6	10.08(7.71)	8.68(5.65)	8.33(5.45)	7.26(5.17)	5.40(4.43)	3.90(3.14)	120
No. of Obs.( $j=1$ )	12(10.00%)	9(7.5%)	16(13.33%)	21(17.50%)	30(25%)	30(25%)	
MBP-AU-6	15.26(8.62)	11.50(7.89)	8.50(5.93)	6.77(5.38)	4.82(4.32)	3.20(3.15)	120
No. of Obs.( $j=1$ )	0(0.00%)	8(6.67%)	14(11.67%)	26(21.67%)	29 (24.17%)	33(27.50%)	

Note: This table summarize average marginal contribution on each unit for different provision mechanisms, in the last 5 periods. Standard deviations are included in the parentheses in rows starting with auction mechanism, e.g., "PYP". We also summarize the frequency of low contributions (individual contribution smaller than 1 experimental dollar); the percentages of the low contributions are included in the parentheses in rows starting with "No. of Obs.( $j=1$ )".

TABLE 1.9: The Counts of Individual Contributions Pivotal on Unit  $j - 1$  and Unit  $j$  if Unit  $j$  can be Provided

<i>Contri. on Unit <math>j - 1</math></i>	Not Pivotal	Pivotal	Not Pivotal	Pivotal
<i>Contri. on Unit <math>j</math></i>	Not Pivotal	Not Pivotal	Pivotal	Pivotal
Unit 1	453	N.A.	N.A.	287
Unit 2	177	4	276	283
Unit 3	78	40	103	559
Unit 4	2	0	116	622
Unit 5	0	0	2	738
Unit 6	0	0	0	740

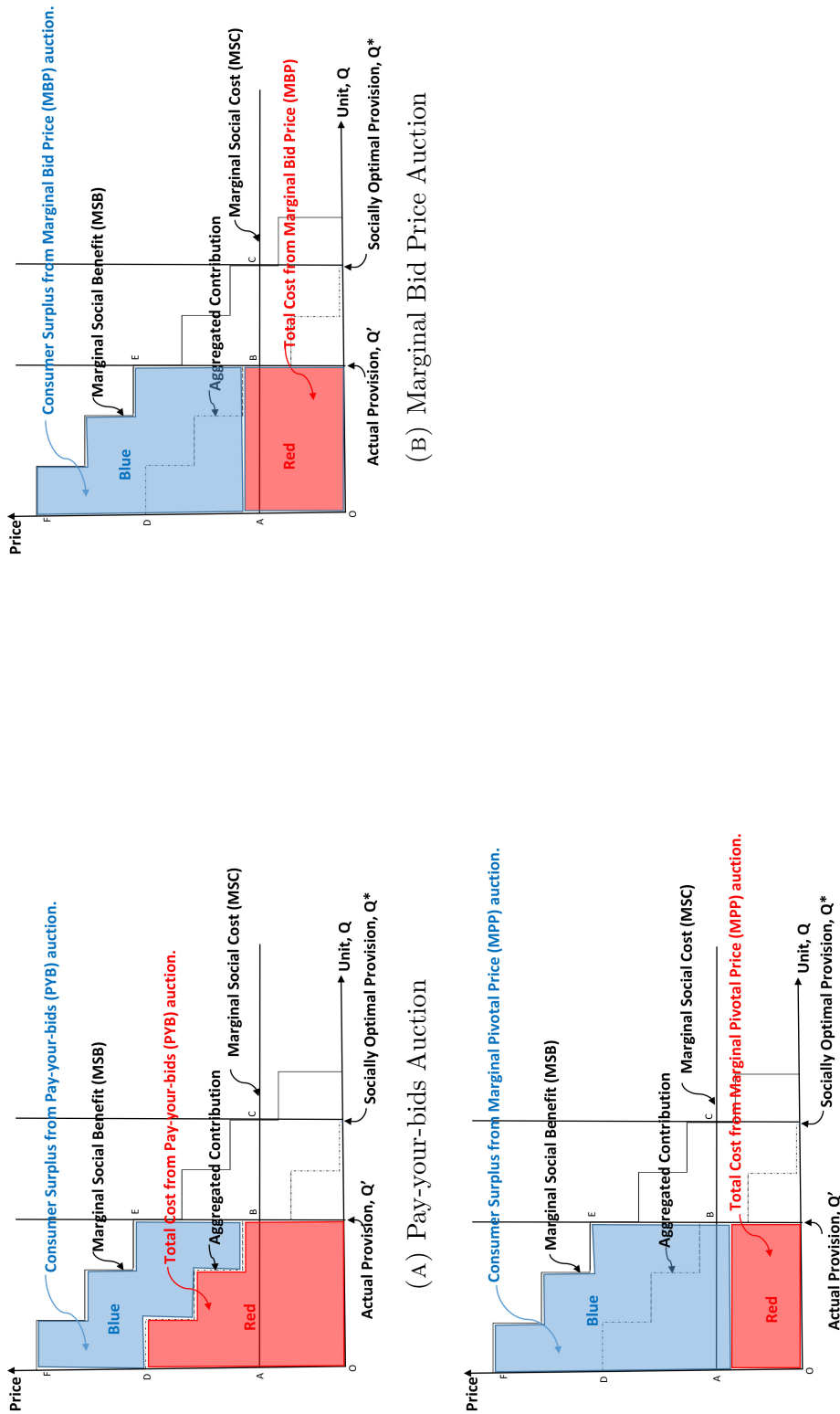
TABLE 1.10: Regression Results: Ascending and Descending Auctions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Unit1	Unit1	Unit2	Unit2	Unit3	Unit3	Unit4	Unit4	Unit5	Unit5	Unit6	Unit6
Value	-0.626*** (0.221)	-0.689*** (0.221)	0.0314 (0.131)	-0.00330 (0.132)	0.343*** (0.0905)	0.261*** (0.0938)	0.381*** (0.128)	0.392*** (0.132)	0.390*** (0.0768)	0.410*** (0.0842)	0.463*** (0.0369)	0.461*** (0.0663)
Value*AU-MBP	(0.0529)	(0.0524)	(0.0374)	(0.0363)	(0.0250)	(0.0245)	(0.0185)	(0.0183)	(0.0127)	(0.0127)	(0.0116)	(0.0116)
	0.0933***		0.147***			0.126***		0.0120		0.00901		0.0453
	(0.0226)		(0.0381)			(0.0342)		(0.0378)		(0.0342)		(0.0750)
Value*AU-MPP		0.00389		-0.152***		0.119***		-0.103**		0.0559		-0.124
	(0.0328)		(0.0506)			(0.0407)		(0.0485)		(0.0441)		(0.0907)
Value*DU-MBP		0.00565		-0.0568		0.0702		0.156***		-0.0185		-0.0230
	(0.0538)		(0.0503)			(0.0453)		(0.0485)		(0.0466)		(0.0896)
Value*DU-MPP		-0.0156		0.000303		0.178***		0.0275		-0.0384		0.0182
	(0.0538)		(0.0498)			(0.0443)		(0.0493)		(0.0454)		(0.0855)
$b^{j-1}$			0.445***	0.571***	0.431***	0.615***	0.424***	0.460***	0.610***	0.558***	0.425***	0.298***
			(0.0178)	(0.0533)	(0.0147)	(0.0452)	(0.0150)	(0.0397)	(0.0146)	(0.0363)	(0.0163)	(0.0402)
$b^{j-1}$ *AU-MBP			-0.273***			-0.242***		-0.0232		0.0336		0.0580
			(0.0577)			(0.0496)		(0.0448)		(0.0398)		(0.0430)
$b^{j-1}$ *AU-MPP			0.0746			-0.124**		0.103*		0.0255		0.260***
			(0.0743)			(0.0583)		(0.0544)		(0.0488)		(0.0510)
$b^{j-1}$ *DU-MBP			0.0847			-0.134**		-0.171***		0.0413		0.138***
			(0.0674)			(0.0558)		(0.0494)		(0.0465)		(0.0487)
$b^{j-1}$ *DU-MPP			-0.114*			-0.183***		-0.0552		0.138***		0.157***
			(0.0675)			(0.0556)		(0.0497)		(0.0454)		(0.0455)
Period	-0.129**	-0.129**	-0.0446	-0.0492	-0.00832	-0.00496	0.0288	0.0240	0.0158	0.0160	0.0296**	0.0293**
Cons.	25.62*** (4.903)	26.36*** (4.866)	3.315 (2.405)	3.329 (2.346)	-1.349 (1.296)	-1.901 (1.283)	-1.825 (1.208)	-2.124* (1.222)	-2.333*** (0.524)	-2.447*** (0.530)	-1.215*** (0.141)	-1.144*** (0.133)
Obs.	1480	1480	1480	1480	1480	1480	1480	1480	1480	1480	1480	1480
Overall $R^2$	0.00259	0.0211	0.366	0.402	0.468	0.495	0.492	0.499	0.650	0.654	0.475	0.499
$\chi^2$	13.92	45.31	634.5	782.3	903.6	1003.7	807.6	846.6	1776.2	1839.2	837.8	939.0

Note: Standard errors in parentheses. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .



FIGURE 1.1: The Realized Social Surplus, Consumers' Surplus and Producers' Net Revenue



(C) Marginal Pivotal Price Auction

Note: The optimal quantity (unit) is denoted by  $Q^*$ , which corresponds to the intersection of the Marginal Social Benefit (MSB) and the Marginal Social Cost (MSC). The actual quantity (units) provided is denoted by  $Q'$ , which corresponds to intersection of the aggregated bid curve and MSC. The blue area represents the consumers' surplus and red area identifies the total cost decided by the actual provision  $Q'$  and the corresponding pricing rules.

FIGURE 1.2: Average Individual Contribution for PYB and MBP-AU: First 5 Periods to Last 5 Periods

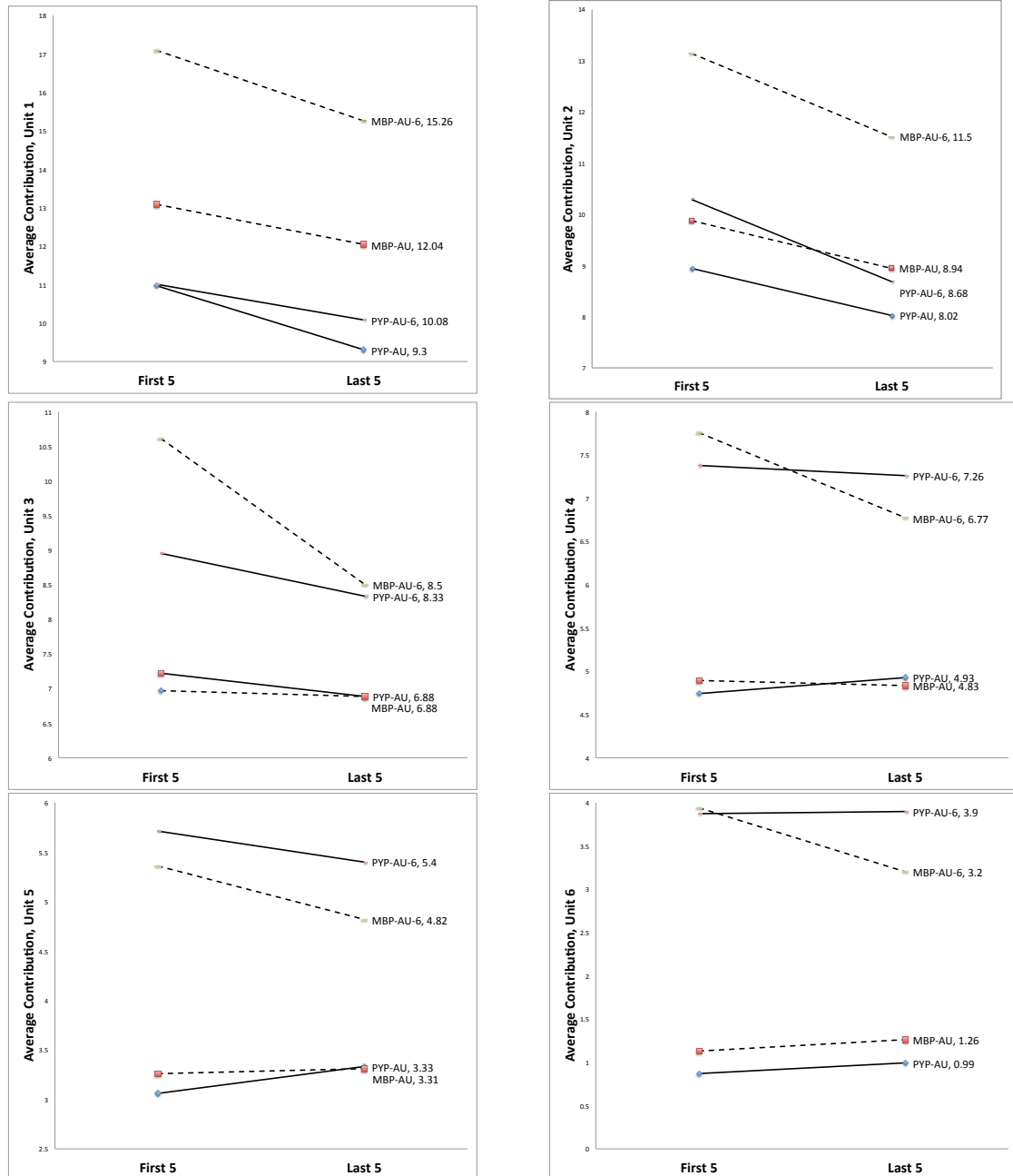
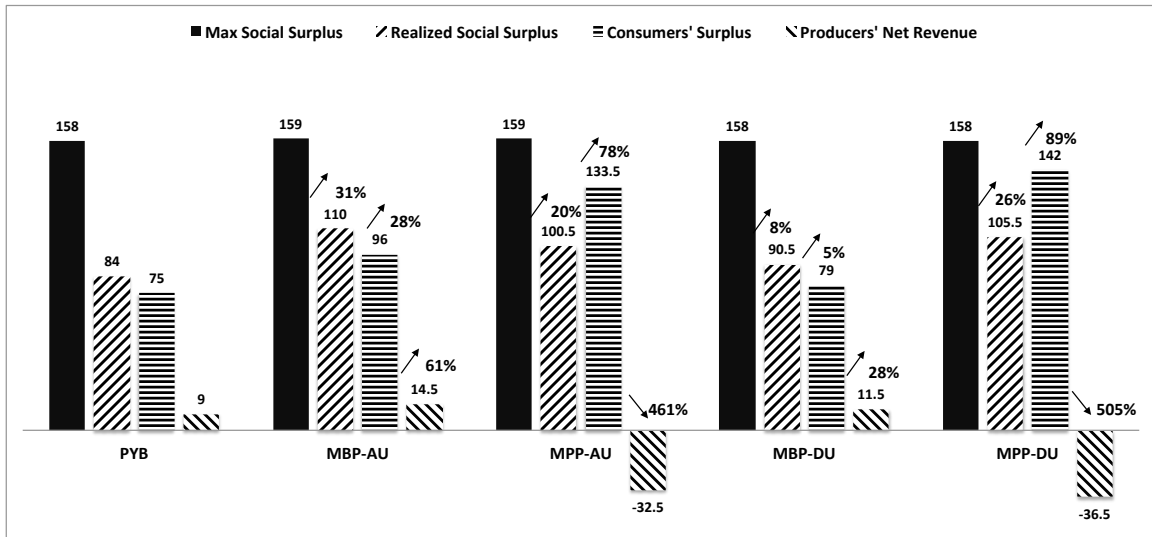
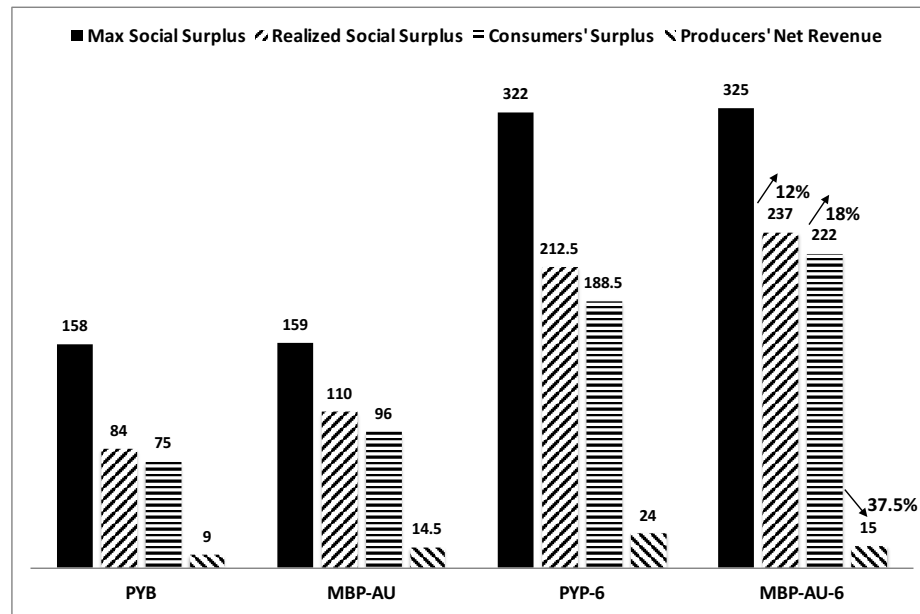


FIGURE 1.3: Experiemntal Results on the Surplus and Surplus Allocation in the Last 5 Periods by Provision Mechanisms



Note: Mann-Whitney  $U$  test are conducted for each IPA with the baseline PYB rule in terms of realized social surplus, consumers' surplus and producers' net revenue. We find that the realized social surplus between PYB/MBP-AU is significant at the 0.05 level ( $p = 0.011, z = 2.552$ ), PYB/MPP-AU is significant at the 0.05 level ( $p = 0.025, z = 2.239$ ). The consumers' surplus between PYB/MBP-AU is significant at the 0.01 level ( $p = 0.0032, z = 2.951$ ), PYB/MPP-AU is significant at 0.01 level ( $p < 0.001, z = 4.248$ ), PYB/MPP-DU is significant at the 0.01 level ( $p < 0.001, z = 3.740$ ). The producers' net revenue between PYB/MPP-AU is significant at the 0.01 level ( $p < 0.001, z = -7.516$ ), PYB/MPP-DU is significant at the 0.01 level ( $p < 0.001, z = 7.482$ ). The omitted comparisons are not significant at 0.1 level.

FIGURE 1.4: Experimental Results on the Surplus and Surplus Allocation in the Last 5 Periods with a Change of Optimal Unit



Note: Mann-Whitney  $U$  test are conducted between the PYB-6 and MBP-AU-6. We find that the realized social surplus between PYB-6/MBP-AU-6 is marginally insignificant at the 0.1 level ( $p = 0.109, z = 1.599$ ); the consumers' surplus between PYB-6/MBP-AU-6 is significant at 0.1 level ( $p = 0.0815, z = 1.742$ ). The producers' net revenue between PYB-6/MBP-AU-6 is significant at 0.05 level ( $p = 0.024, z = 2.252$ ). The percentage values and arrows reflect the relative increase or decrease of surplus compared to PYB-6 for the MBP-AU-6 mechanism.

## Chapter 2

# The Influence of Credit Stacking Programs: The Coexistence of Regional and Global Environmental Markets

### 2.1 Introduction

Environmental and ecosystem service markets represent a frontier for science, policy, and management. These markets may establish financial incentives for production or create demand for environmental credits or off-sets as firms find necessary under regulations regarding mitigation of negative environmental impacts (Alston et al., 2013; Claassen et al., 2008). As environmental markets are incomplete or imperfect, this frontier creates an ambiguity that motivates calls to constrain the functioning of environmental markets.

A particular form for constraint concerns is what may be called "credit stacking"

or "double dipping" (Cooley and Olander, 2011; Fox, 2008). In environmental or ecosystem service markets, credit *stacking* generally refers to a situation where the providers of ecosystem service credits are allowed to sell different types of credits in separate markets, even if these credits are produced from a single management practice, likely on a single parcel of land. With credit stacking permitted, credit productions may overlap spatially for different services. This credit stacking issue partially arises from the jointness in the production, or the "production complementarity" when the landowners could provide environmental benefits from the same management process (Wossink and Swinton, 2007).

Horan et al. (2004) look at the influence of the double dipping policy on the overall social efficiency, depending on how the agri-environmental policy is targeted. In their context, double dipping refers to a situation in which farmers can be paid multiple times by different programs (coordinated or not) for the same environmental improvement, which may be efficient if aggregate marginal payments equal marginal production cost. Woodward (2011) offers a carefully-structured theoretical and quantitative simulation evaluation relating to the economic implications of credit stacking policies. In Woodward's model, a landowner's technology involves a complementarity and a specialization parameter in a joint production function for multiple types of environmental credits. Woodward frames credits stacking as a multiple market (MM) institution allowing the producers to sell jointly produced credits of all types, while framing not allowing credit stacking as a single market (SM) institution, meaning the producers of jointly produced (spatially overlapping) credits must choose one type to sell in the market. Gonzalez-Ramirez and Kling (2015) extend Woodward's model and consider the influence of credit stacking policies in alternative second-best scenarios, focusing on the efficiency loss of uncoordinated policies in different environmental

markets. Valcu et al. (2013) and Yeo et al. (2012) are also relevant to our study as they look at the environmental benefits for both carbon sequestration and water quality improvement through the same agricultural management process. Their studies are empirically based and different from ours in significant ways. Particularly, different from previous studies, we consider the possible impacts of landowners' market participation choices under the SM restriction and analyze how landowners' incentives to participate in different markets affect production of environmental improvements and social efficiency outcomes.

In this research, we focus on the implications when a regional environmental credit is traded under the cap-and-trade framework while the price for a global environmental credit is fixed. Policy implications of similar hybrid market institutions have not been well considered except several recent studies (Ambec and Coria, 2013; Caplan, 2006; Stranlund et al., 2015; Stranlund, 2015), though none of them has studied the influence of policy instrument choices in relation to the market participation incentives in a multiple environmental markets context. Given the prominent importance of carbon sequestration and water quality improvement benefits, environmental market participants may potentially face tradeoffs among multiple environmental markets and consider which or both markets they should participate in and then optimize production accordingly. Montero (2001) considers a permit system that can accommodate multiple pollutants under regulations. In our paper, we provide results when a cap instrument is used to incentivize landowners in the presence of a competitive environmental credit market to provide different types of environmental credits.

We use the water quality credit and carbon sequestration credit as illustrative examples, recognizing when a global market exists for the carbon credit, a single credit producer usually has no influence on the market price. At the same time,

if a regional water quality credit trading market is established by a local regulator, the carbon price and the market participation restrictions (e.g., not allowing credit stacking) could significantly influence the supply and price dynamics in the water quality credit market. We study landowners' market choices in the SM, i.e., which market they decide to participate in when there is a restriction on the number of credit types they can sell for a single project. We also evaluate landowners's profitability in the MM and further evaluate social efficiency implications of the credit stacking policy when a regulatory cap is set for a regional credit market.

Regarding multiple environmental benefits from the same agricultural or environmental management process, previous studies have focused heavily on the co-benefits from carbon credit market. The consequences of environmental co-benefits in the carbon trading markets have been well studied (Caparrós et al., 2010; Feng and Kling, 2005; Feng et al., 2007; Glenk and Colombo, 2011). The credit stacking possibility raises new opportunities to incorporate co-benefits into environmental markets. For example, landowners could have the opportunity to sell all these environmental co-benefits in separate environmental markets so that the landowners would receive revenues from participating in these markets simultaneously, even though the co-benefits are the outcome of the same management practice. Allowing credit stacking, then, would be analogous to sales of jointly produced private goods. A case study on the carbon sequestration co-benefits shows that incorporating co-benefits could improve environment outcomes and increase revenue for farmers in the Upper Mississippi River Basin (Feng et al., 2007), and considering co-benefits may also change the outcome of cost-benefit tests in various soil carbon sequestration (Glenk and Colombo, 2011).

The co-benefits associated with the production of a primary environmental credit have been recognized in other markets as well, such as in the water quality credit



market (Lentz et al., 2014). Liu and Swallow (2016) conduct real water quality credit transactions based on preferences for co-benefits revealed by experiment subjects, and illustrate a way to incorporate public values for environmental co-benefits, as well as water quality improvement, in the Ohio river basin water quality trading market. Their results show that incorporating co-benefits in the water quality trading market could potentially lead to a substantial welfare improvement. In this study, we reconsider the co-benefits questions by theoretically analyzing the overall welfare implications while recognizing the differences in their respective impacts between the carbon and water quality credits and the possibility of un-bundling the primary benefit and the co-benefits from various conservation practices, including agricultural best management practices adopted by farmers to influence the natural production functions.

Existing studies on the credit stacking problem were framed as profit maximization problems where polluters abate several complementary pollutants (Woodward, 2011; Gonzalez-Ramirez and Kling, 2015). However, the credit stacking issue originates from the landowners' eligibility and potential profits from simultaneously participating in multiple environmental markets by supplying environmental credits (Cooley and Olander, 2011; Fox, 2008; Valcu et al., 2013). Landowners could generally provide more cost effective abatement and trade such abatements as environmental credits to regulated industrial polluters when stacking is allowed. For example, the passage of the 1972 and 1977 Federal Water Pollution Control Act Amendments (Clean Water Act, or CWA) do not create any new permitting requirement and preserve agricultural exemptions from permitting, including normal farming practices. Therefore, unregulated landowners could produce water quality credits by improving normal management practices and receive compensations from trading water quality abate-

ment credits to polluters (Horan et al., 1999), who usually face a higher marginal abatement cost compared landowners. For simplicity, we assume a well defined water quality credit in this paper.<sup>1</sup> The differences in marginal abatement cost between landowners and industry polluters provides ample opportunities for water quality credit trading in local areas. The industrial polluters could purchase water quality credits from low-cost abatement entities such as agricultural producers. Also, the polluters usually have to abate a certain amount of water pollution to satisfy the regulatory cap collectively, and thus establish a more or less fixed demand for water quality credits, as long as the credit price is below their marginal abatement cost. Thus, in our context, we assume the water quality regulation drives the demand for the water quality credits and the industrial polluters would purchase credits from low abatement cost providers. It is possible that the polluters could meet the required abatement entirely through trading. Otherwise, the polluters have to satisfy the regulatory cap through their own, more expensive abatement actions.

Water quality trading markets are often coordinated on a regional level (Fisher-Vanden and Olmstead, 2013).<sup>2</sup> The National Resource Conservation Service has been encouraging participation by non-point sources in the water quality market through its Environmental Quality Incentives Program (EQIP),<sup>3</sup> though with a low participation rate national wide. Our results imply that allowing credit stacking could

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<sup>1</sup>Practically, the same unit of water quality credit could have different social value depending the geographical location. The trading ratio approach or potential cost sharing between point-nonpoint trading could further complicate the problem (Horan and Shortle, 2005, 2011; Caplan, 2013). Our paper ignores such practical complications and focuses on the implications of credit stacking policies.

<sup>2</sup>For example, currently active water quality credit trading markets include the Ohio River Basin Trading Project, the Pennsylvania Nutrient Credit Trading, the Chesapeake Bay Watershed Nutrient Credit Exchange, the Red Cedar River Nutrient Trading Pilot (Shortle, 2013). Not all of these regional markets necessarily involve the participations of regulated buyers; some of the markets rely on voluntary offsets and conservation incentivized buyers not under regulatory pressure.

<sup>3</sup>See <http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/financial/eqip/>.

potentially strengthen local water quality trading markets, where credit producers receive increased revenues and profits from selling co-produced environmental credits in other environmental market. Since the greenhouse emission is largely a global issue, in our model, we assume the landowners benefit from participating in a carbon market with a fixed carbon credit price (Weitzman, 2014). This paper does not address question of the relative advantages of a quantity or a price instrument as a market regulatory choice (Ambec and Coria, 2013; Weitzman, 1974; Pizer, 2002; Goulder and Schein, 2013). However, our paper does provide valuable insights into landowners' participation incentives and revenue potentials when they face different policy instruments in environmental markets, with and without the possibility of credit stacking.

Our results show that in the SM institution (where the credit stacking is not allowed), depending on the carbon credit market price (relative to the regulatory trading cap for the water quality credit), several different market participation scenarios might emerge where the landowners with cost advantage in water quality improvement or carbon sequestration choose to participate in different markets. We find when the water quality credit cap is fixed and the carbon credit price exceeds a certain price threshold, the differences between the SM and MM institutions disappear as both types choose to sell in the carbon market and the water quality trading cap fails to influence the landowners' participation and production decisions. We further consider the regulator's choice on the water quality trading cap in the regional environment market, assuming the regulator may or may not fully recognize positive "leakage" from the carbon sequestration benefit (Paltsev, 2001; Baylis et al., 2014) or the policy spillover effect (Ambec and Coria, 2015). Our results indicate that ignoring the carbon sequestration benefit can lead to a substantial loss in the realized social

net benefit. Also, we show that even if the regulator ignores the carbon sequestration benefit, allowing credit stacking by compensating all produced credits still increases net social benefits.

## 2.2 Model

In this section, we present a general model where multiple types of credits are produced simultaneously by landowners. We assume the carbon credit price is exogenous and a landowner is a price taker in the carbon credit market. A landowner's market participation and production decisions will not affect the carbon credit price. The market price for water quality credit can be influenced by the trading cap  $\hat{A}$ , which is set exogenously by a regulator who is primarily concerned about the water quality at a local or regional level. Local polluters, who are subject to effluent regulation, are required to purchase water quality credits ("permits") in order to pollute beyond a certain level. Thus, the polluters are the buyers in the water quality trading market. As a result, the equilibrium price of the water quality credit is determined under a competitive cap-and-trade framework. We assume that for the polluters, buying the water quality credits in the trading market is always cheaper than abating pollution themselves.<sup>4</sup> Since the carbon credit is a global environmental good, here we simply assume a competitive market and ignore the influence of any single supplier.

Landowners are the main providers of environmental credits which could be used

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<sup>4</sup>In other words, we assume the polluters would purchase the water quality credits if the credit price is below a certain price level. Since one motivation of allowing water quality credit trading between agricultural and industrial sectors is the potential cost saving opportunities from the agricultural sector, we assume the cost of buying the traded credits is cheaper than the abatement cost for the polluter. If the market credit price is higher than the abatement cost, the polluters may choose to satisfy the cap entirely through pollution abatement and thus there is no need to establish trading between agricultural and industrial sectors.

to offset pollution. For simplicity, we consider a situation where there are two types of landowners producing water quality and carbon credits. Each type of landowners have the cost advantage in producing one of the relevant credit types. We call the landowners who have a cost advantage in producing carbon credits *type-c*, carbon landowners, and the ones with a cost advantage in producing water quality credits *type-w*, water quality landowners. The market price for carbon credit is denoted by  $\hat{p}$ , which is determined by the carbon price in a global market. The market price for the water quality credit is denoted by  $p_w$ , which is influenced by the trading cap  $\hat{A}$  and the supply of water quality credits in a regional environmental market. For example, the water quality credit price  $p_w$  is the lowest when both types of landowners decide to participate in the water quality market due to a higher aggregated supply. Therefore, the water quality credit price  $p_w$  capture the influence of the aggregated water quality credit supply at a regional level.

We specify a cost function that has been widely in the literature, which assumes production complementarity by interacting the cost of these two credits in the cost function (Woodward, 2011; Antoniou and Kyriakopoulou, 2015; Moslener and Requate, 2007; Stranlund et al., 2015). The role of the regulator is to choose a cap  $\hat{A}$  in the water quality market such that the demand for water quality credits in the market satisfies the overall water quality target, which may not correspond uniquely to the cap since outcomes may be influenced by policy toward credit stacking. Let  $c$  (or  $w$ ) be the amount of carbon (or water quality) credit that a landowner chooses to produce. We use  $g_c$  (or  $g_w$ ) to denote the production cost of the carbon (or the water quality) landowner. The regulator then sets the cap for water quality credit  $\hat{A}$  according to her best knowledge.<sup>5</sup> The carbon credit price will then influence landowners'

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<sup>5</sup>We will discuss the optimal cap choices under various circumstances in Section 2.3. We first

participation and production decisions as it interacts with market dynamics and the resulting price for water quality credits under either the SM or MM stacking policy.

### 2.2.1 Market Outcomes in SM

In the single market (SM) institution where the credit stacking is not allowed, landowners can only choose to sell in one market. For simplicity, we assume that two credit markets coexist with  $N$  homogenous landowners of each type. The cost functions for the landowner specialized in carbon production ( $g_c$ ) and the landowner specialized in water quality production ( $g_w$ ) are:

$$g_c = \frac{\eta}{2}c^2 + \frac{1/\eta}{2}w^2 - \gamma c * w, \quad (2.1)$$

and

$$g_w = \frac{1/\eta}{2}c^2 + \frac{\eta}{2}w^2 - \gamma c * w \quad (2.2)$$

where the specialization parameter  $\eta$  plays a role determining the type of producer, while the complementarity parameter plays an identical role in the cost functions of each type. We assume the complementarity level  $\gamma$  and the specialization level  $\eta$  are both within  $(0, 1)$ . The specialization level increases if the variable  $\eta$  decreases, and the complementarity level increases if the  $\gamma$  increases (Woodward, 2011). Given the water quality credit cap  $\hat{A}$  and the market price of carbon  $\hat{p}$ , the problem faced by

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assume the water quality credit cap  $\hat{A}$  is fixed and the same in SM and MM.

*type-c* landowner (who is specialized in the carbon abatement) is:<sup>6</sup>

$$\max_{j_c} \left\{ m_c : \max_{c,w} \hat{p}c - \left( \frac{\eta}{2}c^2 + \frac{1/\eta}{2}w^2 - \gamma c * w \right); m_w : \max_{c,w} p_w w - \left( \frac{\eta}{2}c^2 + \frac{1/\eta}{2}w^2 - \gamma c * w \right) \right\}, \quad (2.3)$$

where  $j_c \in (m_c, m_w)$  denotes a *type-c* landowner's market participation choice of either choosing the carbon market  $m_c$  or the water quality market  $m_w$ . If  $j_c = m_c$ , the landowner chooses to participate in the carbon credit market and will only receive revenue from producing carbon credits. Note that the landowner may still produce some water quality credits due to production complementarity, but can not sell these water quality credits due to the SM restriction. Interpretations on choosing the water quality market ( $j_c = m_w$ ) are similar. Note that the *type-c* landowner's profit from selling in the water quality market is influenced by the water quality credit price, which is determined by the aggregated supply and the demand of water quality credits. Similarly, the problem faced by the *type-w* landowner (who is specialized in producing water quality credits) is:

$$\max_{j_w} \left\{ m_c : \max_{c,w} \hat{p}c - \left( \frac{1/\eta}{2}c^2 + \frac{\eta}{2}w^2 - \gamma c * w \right); m_w : \max_{c,w} p_w w - \left( \frac{1/\eta}{2}c^2 + \frac{\eta}{2}w^2 - \gamma c * w \right) \right\}, \quad (2.4)$$

where  $j_w$  denotes a *type-w* landowners' market choice to participate in the carbon market,  $j_w = m_c$  or the water quality market,  $j_w = m_w$ .

We set up a model where both types of landowners make the market participation decisions depending on the profit of joining a market. We identify several possible

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<sup>6</sup>Our model assumes  $N$  homogenous landowners of each type (located within the boundary of a regional water quality trading market) and thus each landowner still faces a competitive market price in the water quality market with a trading cap  $\hat{A}$ , similar to the competitive price assumption implied in Woodward (2011) by assuming a representative producer. Thus, each landowner (either the *type-c* or the *type-w*) has little or no influence on the market price  $p_w$  through the change of production. However, the presence of market power in the water quality market (perhaps less likely in carbon market) could potentially complicate our analyses (Hahn, 1984; Liski and Montero, 2006) and is left outside the scope of this analysis.

scenarios: [1] both types choose to sell in the carbon market ( $J_c = m_c, J_w = m_c$ ); [2] both types choose to sell in the water quality carbon market ( $J_c = m_w, J_w = m_w$ ); [3] all *type-c* landowners sell credits in the carbon market while the *type-w* landowners sell credits in the water quality market ( $J_c = m_c, J_w = m_w$ ), [4] all *type-c* landowners sell credits in the water quality market while the *type-w* landowners sell credits in the carbon market ( $J_c = m_w, J_w = m_c$ ), [5] only a percentage  $\tau_1$  of *type-c* landowners sell credits in the water quality market while all *type-w*, water quality landowners sell credits in the water quality market ( $J_c = \tau_1 m_w, J_w = m_w$ ), [6] only a percentage  $\tau_2$  of *type-w* landowners sell credits in the water quality market while the *type-c* landowners sell credits in the carbon market ( $J_c = m_c, J_w = \tau_2 m_c$ ). The notation  $J_c = m_c$  represents the case where all *type-c* landowners choose to sell in the carbon market; the notation  $J_c = \tau_1 m_c$  represents the case where only  $\tau_1 N$  *type-c* landowners choose to sell in carbon market and  $(1 - \tau_1)N$  *type-c* landowners choose to sell in the water quality markets. Other market participation choices  $J_c$  and  $J_w$  are interpreted similarly. The range of the market price for carbon,  $\hat{p}$ , determines which of the above six scenarios applies when multiple markets coexist. As noted before, the water quality price  $p_w$  is determined by aggregated supply and demand in the water quality market.

**Proposition 2.1.** Define  $\hat{p}_1 \equiv \frac{\hat{A}(1-\gamma^2)\eta^2}{N(1+\eta^2)}$ ,  $\hat{p}_2 \equiv \frac{\hat{A}\eta^2(1-\gamma^2)}{N}$ ,  $\hat{p}_3 \equiv \frac{\hat{A}(1-\gamma^2)}{N}$  and  $\hat{p}_4 \equiv \hat{A}(1 - \gamma^2)$ . If  $\hat{p} < \hat{p}_1$ ,  $J_c = m_w, J_w = m_w$ ; if  $\hat{p} \in [\hat{p}_1, \hat{p}_2)$ ,  $J_m = \tau_1 m_w, J_w = m_w$ ; if  $\hat{p} \in [\hat{p}_2, \hat{p}_3)$ ,  $J_c = m_c, J_w = m_w$ ; if  $\hat{p} \in [\hat{p}_3, \hat{p}_4)$ ,  $J_c = m_c, J_w = (1 - \tau_2)m_c$ ; if  $\hat{p} \geq \hat{p}_4$ ,  $J_c = m_c, J_m = m_c$ .

*Proof.* See Appendix. □

Proposition 2.1 identifies the ranges of carbon price, relative to an exogenous water



quality credit cap, under which the market participation choices differ in the SM. Note that each landowner has two options: selling in the carbon market only or the water quality market only. Proposition 2.1 assumes that a landowner will always choose to participate in the market that gives a higher profit. For example, the condition where both types are selling in the water quality market is when a carbon landowner cannot get a higher profit by switching to the carbon market and a water quality landowner cannot get a higher profit by switching to the carbon market. We expect this situation is only likely if the market price for carbon is relatively low, consistent with predictions by Proposition 2.1. Similarly, we can derive the ranges of carbon price where other market participation choices are possible. Detailed calculations can be found in the Appendix.

Figure 2.1 illustrates the market participation choices for both types of landowners as the carbon credit price increases in the SM. When  $\hat{p} < \hat{p}_1$ , the market price for carbon is below a threshold price  $\hat{p}_1$ , both types of landowners sell in the water quality market. As the market price for carbon increases and passes  $\hat{p}_1$ , a carbon landowner may get a higher profit by selling in the carbon market than by selling in the water quality credit market. Therefore, carbon landowners will start to move out of the water quality market until the carbon credit price reaches  $\hat{p}_2$ , where all carbon landowners move out of the water quality credit market and sell in the carbon market. In this situation, both types of landowners will choose to sell in the market for which they enjoy a cost advantage until the price increases to  $\hat{p}_3$ . When the carbon credit price passes  $\hat{p}_3$ , water quality farmers start to move out of the water quality market in pursuit of a higher profit from selling carbon credits and when the carbon credit price increases further to  $\hat{p}_4$ , both types of landowners will choose to sell in the carbon market.

### 2.2.2 Market Outcomes in MM

In the multiple market (MM) institution where the credit stacking is allowed, landowners could produce and sell in both markets. Still, assume the two credit markets coexist and there are  $N$  landowners of each type, the cost functions for the *type-c* landowner  $g_c$  and the *type-w* landowner  $g_w$  are:

$$g_c = \frac{\eta}{2}c^2 + \frac{1/\eta}{2}w^2 - \gamma c * w$$

and

$$g_w = \frac{1/\eta}{2}c^2 + \frac{\eta}{2}w^2 - \gamma c * w.$$

Given the water quality credit cap  $\hat{A}$  and the carbon credit market price  $\hat{p}$ , the problem faced by a *type-c* landowner is:

$$\max_{c,w} \hat{p}c + p_w w - \left( \frac{\eta}{2}c^2 + \frac{1/\eta}{2}w^2 - \gamma c * w \right). \quad (2.5)$$

The problem faced by a *type-w* landowner is:

$$\max_{c,w} \hat{p}c + p_w w - \left( \frac{1/\eta}{2}c^2 + \frac{\eta}{2}w^2 - \gamma c * w \right). \quad (2.6)$$

For any price  $\hat{p}$  and  $p_w$ , the optimal supply function for the *type-c* landowner is:

$$c_c^{MM} = \frac{\hat{p} + p_w \gamma}{1 - \gamma^2}, w_c^{MM} = \frac{\eta p_w + \gamma \hat{p}}{1 - \gamma^2}. \quad (2.7)$$

The optimal supply function for the *type-w* landowner:

$$c_w^{MM} = \frac{\eta\hat{p} + \gamma p_w}{1 - \gamma^2}, w_w^{MM} = \frac{\frac{p_w}{\eta} + \gamma\hat{p}}{1 - \gamma^2}. \quad (2.8)$$

The water quality credit price  $p_w$  is determined by the market clearing condition where the aggregate supply intersects with the demand (the trading cap or the abatement target  $\hat{A}$ ) in the water quality market,

$$p_w = \frac{\hat{A}(1 - \gamma^2) - 2N\gamma\hat{p}}{N(\eta + \frac{1}{\eta})}. \quad (2.9)$$

Note that when  $\hat{p} \geq \frac{\hat{A}(1-\gamma^2)}{2N\gamma}$ , the above equation indicates an unrealistic water quality price below zero, suggesting that when the carbon price is high enough, the landowners will produce enough water quality credits freely and exceed the regulatory cap  $\hat{A}$ . In this situation, since the demand is fixed at the cap, we assume the water quality price falls to zero and

$$p_w = \max \left( \frac{\hat{A}(1 - \gamma^2) - 2N\gamma\hat{p}}{N(\eta + \frac{1}{\eta})}, 0 \right). \quad (2.10)$$

The price of water quality credit could gradually fall close to zero when a high carbon price induces an over supply of water quality credits through complementarity in production.

After deriving the optimal supply function for each type of landowner, we substitute equations (2.7) and (2.8) into the profit functions (2.5) and (2.6), respectively for each type of landowner. Therefore, the *type-c* landowner's profit is:

$$\pi_c^{MM} = \frac{\frac{1}{2\eta}\hat{p}^2 + \gamma\hat{p}p_w + \frac{\eta}{2}p_w^2}{1 - \gamma^2}. \quad (2.11)$$

The profit of the *type-w* landowner is:

$$\pi_w^{MM} = \frac{\frac{\eta}{2}\hat{p}^2 + \gamma\hat{p}p_w + \frac{1}{2\eta}p_w^2}{1 - \gamma^2}. \quad (2.12)$$

where  $p_w$  is specified according to equation (2.10).

### 2.2.3 Equilibrium Prices and Quantities

In our model, the price for the carbon credit is treated as an exogenous variable set by the carbon trading in the global market. The water quality credit price is influenced by the trading cap and the aggregate water quality credit supply in both SM and MM institutions, but the SM incentivizes landowners to focus on one credit type. As a result, the equilibrium water quality price in the SM can be quite different from the price in the MM.

**Proposition 2.2.** *Given the same cap  $\hat{A}$  and the carbon credit price  $\hat{p}$ , the water quality credit price in the MM ( $p_w^{MM}$ ) is no higher than the water quality credit price in the SM ( $p_w^{SM}$ ), i.e.,  $p_w^{MM} < p_w^{SM}$ . Also, the water quality credit price  $p_w^{MM}$  decreases as the carbon credit price  $\hat{p}$  increases in the MM.*

*Proof.* In the MM institution, according to equation (2.10), the water quality credit price is

$$p_w^{MM} = \max \left( \frac{\hat{A}(1 - \gamma^2) - 2N\gamma\hat{p}}{N(\eta + \frac{1}{\eta})}, 0 \right) = \max \left( p_w(m_w, m_w) - \frac{2\gamma\hat{p}\eta}{1 + \eta^2}, 0 \right). \quad (2.13)$$

which is lower than  $p_w(m_w, m_w) = \frac{\hat{A}(1 - \gamma^2)\eta}{(1 + \eta^2)N}$ , the water quality credit price in the SM when both carbon and water quality landowners choose to sell in the water quality

market when the carbon credit price is below a certain threshold. Take the first order derivatives of  $p_w^{MM}(\hat{p})$  with respect to  $\hat{p}$ , we can conclude that:

$$\frac{\partial p_w^{MM}(\hat{p})}{\partial \hat{p}} = \begin{cases} -\frac{2\gamma\eta}{1+\eta^2} & \text{if } \hat{p} < \tilde{p} \\ 0 & \text{if } \hat{p} \geq \tilde{p} \end{cases}. \quad (2.14)$$

where  $\tilde{p} = \frac{\hat{A}(1-\gamma^2)}{2N\gamma}$ , above which the equilibrium water quality credit price falls to zero as  $\hat{A}$  is satisfied due to production complementarity. The above inequality also implies that the water quality credit price will weakly decrease as the carbon price increase in the MM institution. Therefore, the water quality credit price in the MM is no higher than the water quality credit price in the SM, thus we conclude  $p_w^{MM} \leq p_w^{SM}$ .  $\square$

The above results show that MM institution may enable more cost effective abatement approach for polluters who need to purchase water quality credits to satisfy the targeted level of abatement. Another interesting result is that the carbon price and the water quality price move in opposite directions. An increase in the carbon price will bring down the equilibrium water quality credit price, because landowners' participations in the global carbon market effectively subsidize water quality credit production more at a higher carbon credit price. In the MM institution, according to the supply function (2.7) and (2.8), the total water quality credits produced is

$$Q_w^{MM} = Nw_c^{MM} + Nw_w^{MM} = \max\left(\hat{A}, \frac{2N\gamma\hat{p}}{1-\gamma^2}\right) \quad (2.15)$$

while the total carbon credits produced are

$$Q_c^{MM} = \hat{p}N\frac{1+\eta^2}{\eta(1-\gamma^2)} + \max\left(2\gamma(\hat{A} - \frac{2\hat{p}N\gamma}{1-\gamma^2})\frac{\eta}{1+\eta^2}, 0\right), \quad (2.16)$$

The following proposition shows the interconnections between the total carbon credits produced  $Q_c^{MM}$  and the water quality trading cap  $\hat{A}$ .

**Proposition 2.3.** *The total carbon credit produced increases with the carbon price  $\hat{p}$  and the water quality credit cap  $\hat{A}$ , i.e.,  $\frac{\partial Q_c^{MM}}{\partial \hat{A}} > 0$  and  $\frac{\partial Q_c^{MM}}{\partial \hat{p}} > 0$ .*

*Proof.* See Appendix. □

Since  $\frac{\partial Q_c^{MM}}{\partial \hat{A}} > 0$  and  $\frac{\partial Q_c^{MM}}{\partial \hat{p}} > 0$ , either an increase in the carbon price or an increase in the water quality credit cap will lead to more carbon credits in the MM institution. In the SM institution, depending the range of carbon price, the total water quality credits and the carbon credits depend on the landowners' market participation choices.

**Proposition 2.4.** *When the carbon credit price is  $\hat{p}$  and the water quality credit cap is  $\hat{A}$ , the total carbon credits  $Q_c^{SM} \leq Q_c^{MM}$  at any  $\hat{p}$  and  $\hat{A}$ , and the total water quality credits  $Q_w^{SM} \geq Q_c^{MM}$ .*

*Proof.* See Appendix. □

Proposition 2.4 shows that in the SM, when the water quality credit cap is set at  $\hat{A}$ , the production complementarity may enable a higher total water quality credit production exceeding the trading cap  $\hat{A}$ , when the two types choose to sell in different markets. The amount of positive leakage equals the production of water quality credits “unintentionally” produced by the landowners choose to sell in the carbon market. We also find that the total carbon credit produced in SM is always lower than the carbon credit produced in MM, in contrast to a higher water quality credits produced from the SM. When the carbon credit price increases beyond a threshold price  $\tilde{p} = \frac{\hat{A}(1-\gamma)}{2N\gamma}$ , the SM and MM institutions lead to identical carbon and water

quality credits productions. In this situation, water quality credits produced in both the SM and MM will exceed the cap  $\hat{A}$ . Note that the above results hold when the carbon credit price  $\hat{p}$  and the water quality credit cap  $\hat{A}$  are the same in SM and MM.

## 2.3 The Social Welfare Implications of Alternative Credit Stacking Policies

In the carbon market, we assume that the market equilibrium price  $\hat{p}$  is always fixed and thus a single landowner has no influence on the market price either through market participation decisions or change of production. Depending on the market price for the carbon credit, the SM and MM stacking policies could lead to different welfare implications. We assume the regulator can choose different water quality credit caps in the SM and MM institutions.

### 2.3.1 The First-Best Benchmark

In the first-best world, the optimal supplies  $(c_i^*, w_i^*)$  and  $(c_k^*, w_k^*)$  maximize the following social net benefit function

$$NB = B_c(\sum_i c_i + \sum_k c_k) + B_w(\sum_i w_i + \sum_k w_k) - \left( \sum_{i=1}^N g_{ci}(c_i, w_i) + \sum_{k=1}^N g_{wk}(c_k, w_k) \right), \quad (2.17)$$

where the  $B_c(\cdot)$  and  $B_w(\cdot)$  are the benefit functions for carbon credit and water quality improvement, respectively, with  $B'_t(\cdot) > 0$  and  $B''_t(\cdot) \leq 0$  where  $t = c, w$ . The subscript  $i$  indexes the carbon landowners and the subscript  $k$  indexes the water quality landowners, thus,  $g_{ci}(\cdot)$  is the cost function for carbon landowner  $i$  and  $g_{wk}(\cdot)$  is the cost function for water quality landowner  $k$ . For simplicity, we assume a

constant marginal carbon sequestration benefit  $d_c$  at the market price  $\hat{p}$  and a constant water quality improvement benefit  $d_w$ . Therefore, the first order conditions imply  $\hat{p} = d_c = \frac{\partial g_{ci}}{\partial c_i} = \frac{\partial g_{wk}}{\partial c_k}$  and  $d_w = \frac{\partial g_{ci}}{\partial w_i} = \frac{\partial g_{wk}}{\partial w_k}$ .

### 2.3.2 Maximize Carbon Sequestration and Water Quality Benefits

In our context, we first assume the water quality credit cap is chosen so that the benefits from carbon sequestration and water quality pollution abatement are maximized. The regulator's cap choice is denoted as  $A_r$ . Therefore, the regulator chooses  $A_r$  to maximize the total net social benefit function,

$$\begin{aligned} NB(A_r) &= B_c(Q_c(A_r)) + B_w(Q_w(A_r)) \\ &- \left( \sum_{i=1}^N g_{ci}(c_i(A_r), w_i(A_r)) + \sum_{k=1}^N g_{wk}(c_k(A_r), w_k(A_r)) \right), \end{aligned} \quad (2.18)$$

where the total carbon credits produced  $Q_c(A_r) = \sum_{i=1}^N c_i(A_r) + \sum_{k=1}^N c_k(A_r)$  and the water quality credits produced  $Q_w(A_r) = \sum_{i=1}^N w_i(A_r) + \sum_{k=1}^N w_k(A_r)$ . Note that the above benefit function could also written

$$\begin{aligned} NB(A_r) &= \hat{p}Q_c(A_r) + B_w(Q_w(A_r)) \\ &- \left( \sum_{i=1}^N g_{ci}(c_i(A_r), w_i(A_r)) + \sum_{k=1}^N g_{wk}(c_k(A_r), w_k(A_r)) \right), \end{aligned} \quad (2.19)$$

which is the profit maximization problem where a benevolent regulator cares about the landowners' total revenue from carbon credits and the benefit from the local water quality improvement, even though the regulator may not care about environmental benefit of carbon sequestration locally or globally.



Based on the first order condition, an optimal cap  $A_r = A^*$  is chosen when

$$\begin{aligned} & B'_c(Q_c(A_r)) Q'_c(A_r) + B'_w(Q_w(A_r)) Q'_w(A_r) \\ = & \sum_{i=1}^N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_r)}{\partial A_r} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_r)}{\partial A_r} \right) + \sum_{k=1}^N \left( \frac{\partial g_{wk}}{\partial c_k} \frac{\partial c_k(A_r)}{\partial A_r} + \frac{\partial g_{wk}}{\partial w_k} \frac{\partial w_k(A_r)}{\partial A_r} \right). \end{aligned} \quad (2.20)$$

Substitute the credit production  $Q_c(A_r) = \sum_{i=1}^N c_i(A_r) + \sum_{k=1}^N c_k(A_r)$  and  $Q_w(A_r) = \sum_{i=1}^N w_i(A_r) + \sum_{k=1}^N w_k(A_r)$ , we can also get,

$$\begin{aligned} & \sum_{i=1}^N \left( \left( \hat{p} - \frac{\partial g_{ci}}{\partial c_i} \right) \frac{\partial c_i(A_r)}{\partial A_r} + \left( d_w - \frac{\partial g_{ci}}{\partial w_i} \right) \frac{\partial w_i(A_r)}{\partial A_r} \right) \\ + & \sum_{k=1}^N \left( \left( \hat{p} - \frac{\partial g_{wk}}{\partial c_k} \right) \frac{\partial c_k(A_r)}{\partial A_r} + \left( d_w - \frac{\partial g_{wk}}{\partial w_k} \right) \frac{\partial w_k(A_r)}{\partial A_r} \right) = 0. \end{aligned} \quad (2.21)$$

In the MM, for each landowner  $i$  (*type-c*) or  $k$  (*type-w*), according to the profit maximization behavior, we have  $\hat{p} = \frac{\partial g_{ci}}{\partial c_i} = \frac{\partial g_{wk}}{\partial c_k}$  and  $p_w(A_r) = \frac{\partial g_{ci}}{\partial w_i} = \frac{\partial g_{wk}}{\partial w_k}$ . Therefore, the MM leads to a first-best outcome if  $p_w^{MM} = d_w$ . In the SM with market participation constraints, for a landowner  $i$  ( $k$ ), either  $\hat{p} = \frac{\partial g_{ci}}{\partial c_i}$  ( $\hat{p} = \frac{\partial g_{wk}}{\partial c_k}$ ) or  $d_w = \frac{\partial g_{ci}}{\partial w_i}$  ( $d_w = \frac{\partial g_{wk}}{\partial w_k}$ ) holds. Therefore, the SM is a restriction that can prevent the society from achieving a first-best outcome, which can be obtained from the unconstrained maximization in the MM if  $p_w^{MM}(A_r) = d_w$ . Below we derive the optimal cap choice  $A_r$  in MM as well as in SM when market choices are restricted and show the  $p_w^{MM}(A_r) = d_w$  in the MM when the regulator cares about both carbon and water quality benefit.

**Proposition 2.5.** *If the regulator considers both carbon and water quality benefit when choosing the cap  $A_r$ , the optimal cap choice in the MM is*

$$A_r^{MM} = \frac{d_w(\eta + \frac{1}{\eta}) + 2\gamma\hat{p}}{1 - \gamma^2} N, \quad (2.22)$$

*and the water quality credit price equals the marginal benefit of water quality improve-*

ment,  $p_w^{MM} = d_w$ . The optimal cap choices in the SM are

$$A_r^{SM} = \begin{cases} \frac{d_w(\eta + \frac{1}{\eta}) + 2\gamma\hat{p}}{1-\gamma^2} N & \text{if } \hat{p} < \frac{d_w\eta}{2-\gamma} \\ \left( \frac{(N+\eta^2)d_w}{(1-\gamma^2)(2-\gamma)\eta}, \frac{N(1+\eta^2)d_w}{(1-\gamma^2)(2-\gamma)\eta} \right) & \text{if } \hat{p} = \frac{d_w\eta}{2-\gamma} \\ \frac{d_w\frac{1}{\eta} + \gamma\hat{p}}{1-\gamma^2} N & \text{if } \hat{p} \in \left( \frac{d_w\eta}{2-\gamma}, \frac{d_w\eta}{2\eta^2-\gamma} \right) , \\ \left( \frac{d_w\eta}{(2\eta^2-\gamma)(1-\gamma^2)}, \frac{Nd_w\eta}{(2\eta^2-\gamma)(1-\gamma^2)} \right) & \text{if } \hat{p} = \frac{d_w\eta}{2\eta^2-\gamma} \\ \frac{d_w\eta}{(2\eta^2-\gamma)(1-\gamma^2)} & \text{if } \hat{p} > \frac{d_w\eta}{2\eta^2-\gamma} \end{cases} \quad (2.23)$$

the water quality credit price equals the marginal benefit of water quality improvement plus the marginal influence of cap choice on the benefit of carbon ,  $p_w^{SM} = d_w + \hat{p}Q'_c(A_r)$ .

According to Proposition 2.5, the equilibrium water quality price in the MM  $p_w^{MM} = d_w$ . Therefore, MM leads to a first-best best outcome when the regulator can choose a cap to maximize both carbon and water quality benefit.

**Proposition 2.6.** *When the regulator cares both carbon sequestration and water quality improvement benefit and choose the regulatory cap optimally, the realized net social benefit in MM  $NB_{MM}$  is always higher than or equal to  $NB_{SM}$ , the realized net social benefit in SM.*

*Proof.* See Appendix. □

### 2.3.3 Maximize Water Quality Benefits

Alternatively, we assume a local regulator cares *only* about the benefits from water quality pollution abatement. Thus, we assume a second-best condition where the cap is chosen so that the benefits from water quality pollution abatement are maximized.

The regulator's cap choice is denoted as  $A_{r'}$ . Therefore, the regulator chooses  $A_{r'}$  that maximizes the net social benefit function,

$$NB(A_{r'}) = d_w(Q_w(A_{r'})) - \left( \sum_{i=1}^N g_{ci}(c_i(A_{r'}), w_i(A_{r'})) + \sum_{k=1}^N g_{wk}(c_k(A_{r'}), w_k(A_{r'})) \right), \quad (2.24)$$

where the water quality improvement produced  $Q_w(A_{r'}) = \sum_{i=1}^N w_i(A_{r'}) + \sum_{k=1}^N w_k(A_{r'})$ , the  $B_w(\cdot)$  is the benefit function for water quality improvement. Based on the first order condition, an optimal cap  $A_{r'}$  is chosen when

$$\begin{aligned} & B'_w(Q_w(A_{r'})) Q'_w(A_{r'}) \\ &= \sum_{i=1}^N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_{r'})}{\partial A_{r'}} \right) + \sum_{k=1}^N \left( \frac{\partial g_{wk}}{\partial c_k} \frac{\partial c_k(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{wk}}{\partial w_k} \frac{\partial w_k(A_{r'})}{\partial A_{r'}} \right). \end{aligned} \quad (2.25)$$

The second-best condition is achieved if the  $A_{r'}$  is chosen such that the above equation (2.25) holds, or

$$\begin{aligned} & \sum_{i=1}^N \left( \left(0 - \frac{\partial g_{ci}}{\partial c_i}\right) \frac{\partial c_i(A_r)}{\partial A_r} + \left(d_w - \frac{\partial g_{ci}}{\partial w_i}\right) \frac{\partial w_i(A_r)}{\partial A_r} \right) \\ &+ \sum_{k=1}^N \left( \left(0 - \frac{\partial g_{wk}}{\partial c_k}\right) \frac{\partial c_k(A_r)}{\partial A_r} + \left(d_w - \frac{\partial g_{wk}}{\partial w_k}\right) \frac{\partial w_k(A_r)}{\partial A_r} \right) = 0. \end{aligned} \quad (2.26)$$

Compared to the equation (2.21), even the MM could not achieve the first-best outcome since the cap chosen from maximizing equation (2.24) could not satisfy the equation (2.21). Both MM and SM lead to second-best outcomes when the regulator cares only about the water quality benefit.

**Proposition 2.7.** *If the regulator only considers water quality benefits when choosing the cap choice  $A_r$ , the “second-best” cap choice in the MM is*

$$A_{r'}^{MM} = \frac{d_w(\eta + \frac{1}{\eta})}{1 - \gamma^2} N, \quad (2.27)$$

*which is smaller than the optimal cap choice  $A_r^{MM}$ . The water quality credit price*

equals the marginal benefit of water quality improvement minus the marginal influence of cap choice on the carbon benefit,  $p_w^{MM} = d_w - \hat{p}Q'_c(A_{r'})$ .

The “second-best” cap choices in the SM are

$$A_r^{SM} = \begin{cases} \frac{d_w(\eta + \frac{1}{\eta})}{1-\gamma^2} N & \text{if } \hat{p} < d_w\eta \\ \left( \frac{(N+\eta^2)d_w}{(1-\gamma^2)\eta}, \frac{N(1+\eta^2)d_w}{(1-\gamma^2)\eta} \right) & \text{if } \hat{p} = d_w\eta \\ \frac{d_w \frac{1}{\eta}}{1-\gamma^2} N & \text{if } \hat{p} \in (d_w\eta, \frac{d_w}{\eta}) \\ \left( \frac{d_w}{(1-\gamma^2)\eta}, \frac{Nd_w}{(1-\gamma^2)\eta} \right) & \text{if } \hat{p} = \frac{d_w}{\eta} \\ \frac{d_w}{(1-\gamma^2)\eta} & \text{if } \hat{p} > \frac{d_w}{\eta} \end{cases}, \quad (2.28)$$

and the water quality credit price equals the marginal benefit of water quality improvement,  $p_w^{SM} = d_w$ .

Figure 2.2 shows the optimal water quality credit cap choices under various circumstances. We conclude that all other thing being equal, the optimal caps are always higher when the regulator considers both carbon sequestration and water quality improvement benefits or when credit stacking is allowed.

**Proposition 2.8.** *When the regulator only considers water quality benefit when choosing the cap choice  $A_{r'}$ , the MM leads to a higher social net benefit compared to SM except when  $\hat{p} \geq \max(\frac{d_w(1+\eta^2)}{2\eta\gamma}, \frac{d_w}{\eta})$ , the MM leads to the same net social benefit compared to SM.*

*Proof.* See Appendix. □

Proposition 2.8 shows even if the regulator ignores the carbon sequestration benefit in choosing the water quality credit cap, the MM still leads to a strictly higher net social benefit in most cases. However, if the carbon credit price (the marginal benefit

of carbon abatement)  $\hat{p} \geq \max(\frac{d_w(1+\eta^2)}{2\eta\gamma}, \frac{d_w}{\eta})$ , the MM will lead to a same net social benefit. Figure 2.3 shows that the overall net social benefit as the carbon credit price changes in different scenarios. Not surprisingly, the loss in the social net benefit is increasing with the carbon credit price when the regulator ignores the carbon sequestration benefits. Also, when the regulator ignores the carbon sequestration benefit, the MM performs weakly better than SM.

## 2.4 Conclusions and Discussion

Our research shows how the restrictions on market participation choices (e.g., the limitation imposed by the SM institution on the number of markets to participate) can lead to significantly different market outcomes where multiple environmental markets co-exist. According to our specification, allowing credit stacking (the MM institution) leads to a higher social surplus when the water quality credits are sold to polluters facing a regulatory cap (and high abatement costs at the source) and the carbon credit price is exogenous when the regulator considers both carbon sequestration and water quality improvement benefit in choosing the cap. We show that the regulator forgoes a substantial amount of net social benefit if the carbon sequestration benefit is ignored. Also, our research demonstrates how the cap choice for one credit and the market price of another credit can jointly influence landowners' market participation and production choices, assuming price taking behaviors. These relationships are important for designing a comprehensive, inter-connected environmental market where multiple types of environmental credits are traded at the same time. Currently, many environmental markets focus on the provision of only one type of credit and may

lead to over-provision of certain types of credit if the regulator fails to consider the complementarity in the natural production process. Such over-provision potentially decreases the production of other goods or benefit, including perhaps more valuable environmental benefits.

To establish functional environmental markets with multiple types of credits can be particularly challenging. If the cap-and-trade framework is applied to some markets, an inappropriate choice on the cap will lead to distortions in other environmental markets. Furthermore, the complementarity that exists in production could even magnify the efficiency loss from an incorrectly chosen cap compared to a baseline where environmental markets are assumed to be isolated from one another. Also, the process of establishing multiple markets many require significant efforts from policy makers and may face many legislation challenges. One particular challenge may come from polluters. The establishment of multiple credit markets requires specific regulations on these credits, and such regulations will likely increase the abatement or transaction cost of producers. However, when credit producers are allowed to sell all types of credits, the per unit cost of a credit is likely to decrease, such as a lower water quality price in the MM shown in this study. Thus, from the perspective of the polluters, the overall compliance cost may actually decrease, or from the perspective of the society, such lower net costs may push the balance of marginal costs and benefits toward a higher environmental quality.

We assume a specific functional form for the credit producers' cost functions. 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. However, we expect our results hold

for more generalized functional forms with production complementarity.

In order to calculate the optimal cap choices, we make simplifying assumptions regarding the regulator's information, and assume the regulator could choose the trading cap correctly with the benefit information such as  $B_c(\cdot)$  and  $B_w(\cdot)$  available. Depending on the pre-existing distortions in different second-best scenarios (Fullerton and Metcalf, 2001; Holland, 2009; Lipsey and Lancaster, 1956), the SM might perform better than MM policy (Gonzalez-Ramrez and Kling, 2015; Woodward, 2011). The problem of designing a functional environmental credit trading system is of crucial interest to environmental economists. Current discussions and debates surrounding the credit stacking policy only reflect one aspect of potential challenges. A full understanding of the credit trading system needs more theoretical research on the choice of an optimal institution, which can be region specific or a mixed combination of current trading institutions, such as a hybrid design incorporating SM and MM designs in the presence of market distortions. On the other hand, practical considerations such as how to encourage landowners' participations, how to incentivize landowners beside monetary compensations and how to impose appropriate regulations on polluters and enforce compliance standards are also important to encourage participations and transactions in environmental markets. More research in the above areas could be helpful to improve the trading rules and enhance the efficiency for multiple environmental markets.

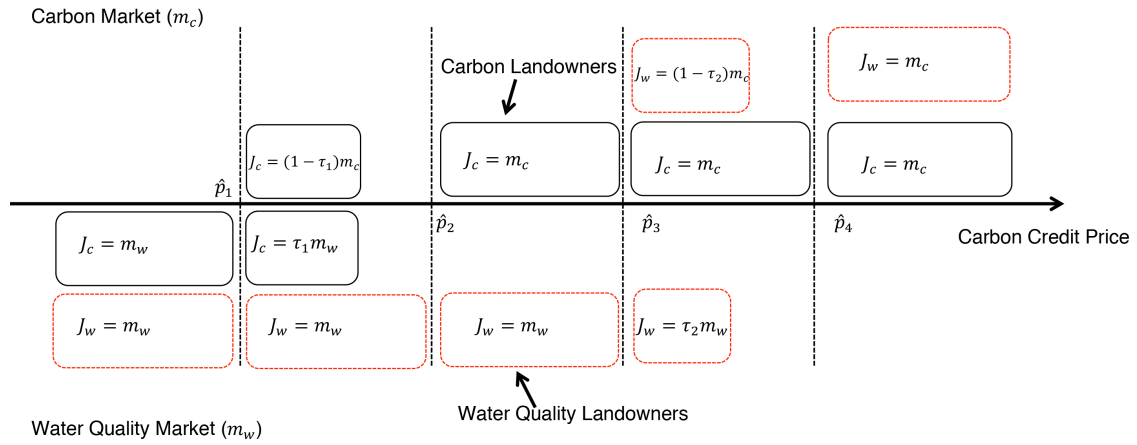
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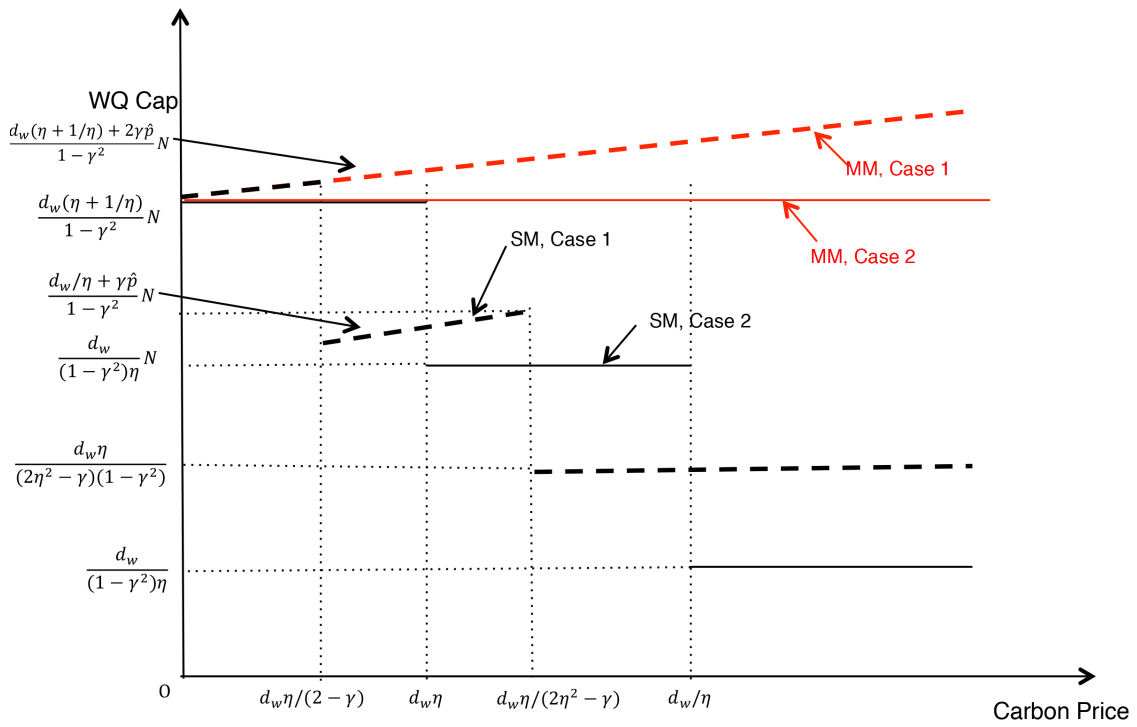


FIGURE 2.1: Market Participation Choices in SM.



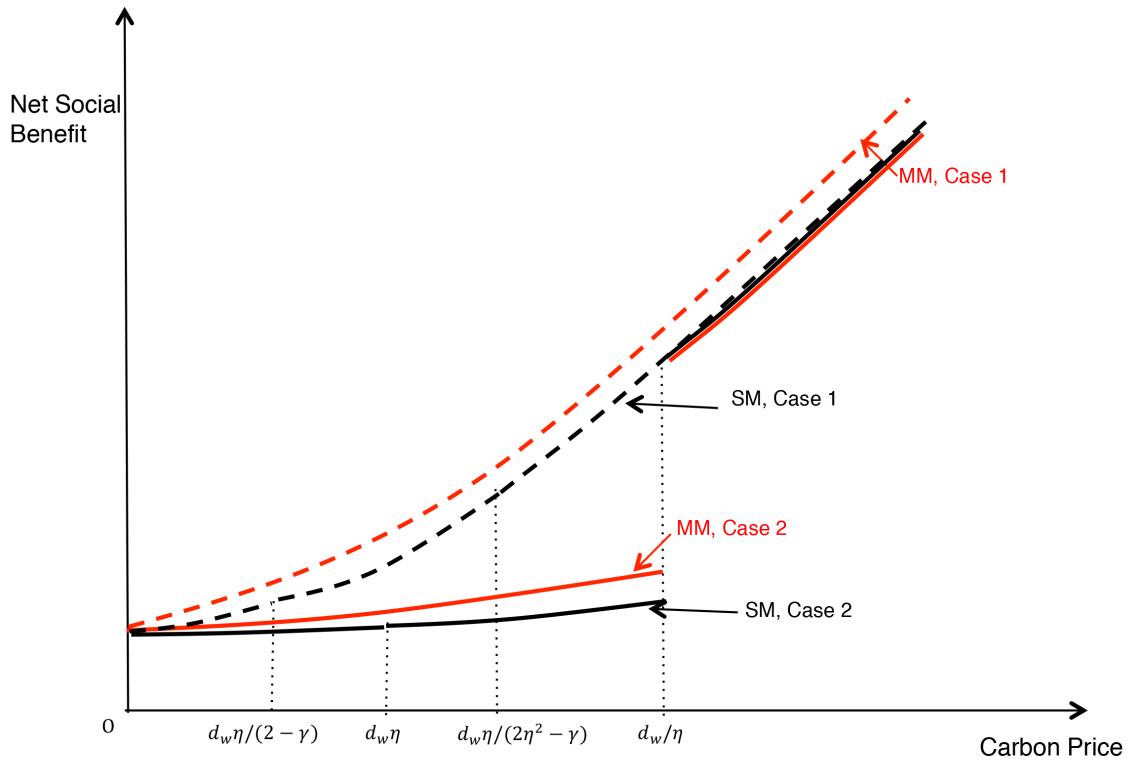
Note: This figure shows the market participation choices depending on the carbon credit price  $\hat{p}$ . The solid rectangles represent the carbon landowners; the dotted rectangles represent the water quality landowners. The size of the rectangles reflects the percentage of carbon or water quality landowners' choices to participate in the carbon market ( $m_c$ ) or the water quality market ( $m_w$ ).

FIGURE 2.2: Water Quality Credit Cap Choice in MM and SM.



Note: This figure shows the regulator's water quality credit cap choice in MM and SM. Case 1 shows the situation where the regulator cares about both the carbon sequestration and water quality improvement benefits. Case 2 shows the situation where the regulator cares only about the water quality improvement benefits.

FIGURE 2.3: Social Net Benefit in MM and SM.



Note: This figure shows the realized social net benefit in MM and SM. Case 1 shows the situation where the regulator cares about both the carbon sequestration and water quality improvement benefits. Case 2 shows the situation where the regulator cares only about the water quality improvement benefits.

## Appendix

**Proof for Proposition 2.1** We solve the landowners' market participation choices in the SM assuming that a landowner will always choose the market that returns a higher profit.

**Expected Profit** Conditional on the market participation choices, a *type-c* landowner chooses production  $(c_c^{SM}, w_c^{SM})$  to maximize profit. If  $j_c = m_c$ , a *type-c* landowner chooses to participate in the carbon market and the corresponding profit function is:

$$\max_{c_c^{SM}, w_c^{SM}} \hat{p}c - \left(\frac{\eta}{2}c^2 + \frac{1/\eta}{2}w^2 - \gamma c * w\right). \quad (2.29)$$

As a result, the optimal production can be expressed as:

$$c_c^{SM}(m_c) = \frac{\hat{p}}{(1 - \gamma^2)\eta}, w_c^{SM}(m_c) = \frac{\gamma\hat{p}}{1 - \gamma^2}. \quad (2.30)$$

If  $j_c = m_w$ , then a *type-c* landowner's profit function is:

$$\max_{c_c^{SM}, w_c^{SM}} p_w w - \left(\frac{\eta}{2}c^2 + \frac{1/\eta}{2}w^2 - \gamma c * w\right) \quad (2.31)$$

In this case, the optimal supply functions are

$$c_c^{SM}(m_w) = \frac{\gamma p_w}{1 - \gamma^2}, w_c^{SM}(m_w) = \frac{p_w \eta}{1 - \gamma^2} \quad (2.32)$$

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

Similarly, conditional on the market participation choice  $j_c$  or  $j_w$ , a *type-w* landowner chooses production  $(c_w^{SM}, w_w^{SM})$  to maximize profit. If  $j_w = m_c$ , then a *type-w* landowner's optimal supply functions are:

$$c_w^{SM}(m_c) = \frac{\hat{p}\eta}{1 - \gamma^2}, w_w^{SM}(m_c) = \frac{\gamma\hat{p}}{1 - \gamma^2}. \quad (2.33)$$

If  $j_w = m_w$ , then a *type-w* landowner's supply functions are:

$$c_w^{SM}(m_w) = \frac{\gamma p_w}{1 - \gamma^2}, w_w^{SM}(m_w) = \frac{p_w}{(1 - \gamma^2)\eta}, \quad (2.34)$$

Denote the profit of the carbon landowner selling in the carbon market as  $\pi_c(m_c)$ , the profit of the carbon landowner selling in the water quality market is denoted as  $\pi_c(m_w)$ . Similarly, denote the profit of the water quality landowner by  $\pi_w(m_c)$  and  $\pi_w(m_w)$ , which depends on the market participation choice. Thus we have,

$$\pi_c(m_c) = \frac{\hat{p}^2}{2(1 - \gamma^2)\eta}, \quad (2.35)$$

or

$$\pi_c(m_w) = \frac{p_w^2\eta}{2(1 - \gamma^2)}. \quad (2.36)$$

For a water quality landowner who sells in the water quality market, the profit is:

$$\pi_w(m_w) = \frac{p_w^2}{2(1 - \gamma^2)\eta}, \quad (2.37)$$

If a water quality landowner chooses to sell in the carbon market, the profit is:

$$\pi_w(m_c) = \frac{\hat{p}^2\eta}{2(1 - \gamma^2)}. \quad (2.38)$$

**Market Participation Choices** Based on the conditional profits, all carbon landowners participate in the carbon market ( $J_c = m_c$ ) if

$$\pi_c(m_c) > \pi_c(m_w) \Rightarrow \hat{p} > p_w \eta; \quad (2.39)$$

all carbon landowners participate in the water quality market ( $J_c = m_w$ ) if

$$\pi_c(m_c) < \pi_c(m_w) \Rightarrow \hat{p} < p_w \eta; \quad (2.40)$$

furthermore,  $\tau_1 N$  ( $0 < \tau_1 < 1$ ) carbon landowners participate in the water quality market ( $J_c = \tau_1 m_w$ ) if

$$\pi_c(m_c) = \pi_c(m_w) \Rightarrow \hat{p} = p_w \eta; \quad (2.41)$$

Similarly, all water quality landowners participate in the carbon market ( $J_w = m_c$ ) if

$$\pi_w(m_c) > \pi_w(m_w) \Rightarrow \hat{p} > \frac{p_w}{\eta}; \quad (2.42)$$

all water quality landowners participate in the water quality market ( $J_w = m_w$ ) if

$$\pi_w(m_c) < \pi_w(m_w) \Rightarrow \hat{p} < \frac{p_w}{\eta}; \quad (2.43)$$

furthermore,  $\tau_2 N$  ( $0 < \tau_1 < 1$ ) water quality landowners participate in the water quality market ( $J_w = \tau_2 m_w$ ) if

$$\pi_w(m_c) = \pi_w(m_w) \Rightarrow \hat{p} = \frac{p_w}{\eta}; \quad (2.44)$$

Since  $\eta \in (0, 1)$ ,  $p_w \eta < \frac{p_w}{\eta}$  and when  $\hat{p} < p_w \eta$ , both types of landowners will choose

to participate in the water quality market. When  $\hat{p} > \frac{p_w}{\eta}$ , both types of landowners will choose to participate in the carbon credit market. When  $\hat{p} \in [p_w\eta, \frac{p_w}{\eta}]$ , some landowners will participate in one market and some will participate in the other market.

**Water Quality Credit Price  $p_w$**  In the market equilibrium, the water quality credit price  $p_w$  is determined by the aggregated supply and the demand. Specifically, when  $\hat{p} < p_w\eta$ , both the *type-w* and *type-c* landowners are selling in the water quality credit market, therefore, the market clearing condition is

$$Nw_c^{SM}(m_w) + Nw_w^{SM}(m_w) = \hat{A}, \quad (2.45)$$

thus,

$$p_w = \frac{\hat{A}(1 - \gamma^2)\eta}{(1 + \eta^2)N}. \quad (2.46)$$

Therefore, when  $\hat{p} < \frac{\hat{A}(1-\gamma^2)\eta^2}{(1+\eta^2)N}$ , both types will choose to sell in the water quality market.

As the carbon price  $\hat{p}$  increases, it is possible  $\hat{p} = p_w\eta$  and some carbon landowners,  $\tau_1 N$  will choose to sell in the water quality market and  $(1 - \tau_1)N$  will choose to sell in the carbon market, the market clearing condition is

$$\tau_1 Nw_c^{SM}(m_w) + Nw_w^{SM}(m_w) = \hat{A}, \quad (2.47)$$

thus,

$$p_w = \frac{\hat{A}(1 - \gamma^2)\eta}{(1 + \tau_1\eta^2)N}. \quad (2.48)$$

Therefore, when  $\hat{p} \in [\frac{\hat{A}(1-\gamma^2)\eta^2}{(1+\eta^2)N}, \frac{\hat{A}(1-\gamma^2)\eta^2}{N})$ ,  $\tau_1 N$  carbon landowners will choose to sell in the water quality market and all water quality landowners will choose to sell in the water quality market with  $\tau_1 = \frac{\hat{A}(1-\gamma^2)}{\hat{p}N} - \frac{1}{\eta^2}$ .

When the carbon price  $\hat{p}$  further increases and  $\hat{p} \in [\frac{\hat{A}(1-\gamma^2)\eta^2}{N}, \frac{A(1-\gamma^2)}{N})$ , all carbon landowners will choose to sell in the carbon market and all water quality landowners will choose to sell in the water quality market. In this situation, the market clearing condition is,

$$Nw_w^{SM}(m_w) = \hat{A}, \quad (2.49)$$

and

$$p_w = \frac{\hat{A}(1-\gamma^2)\eta}{N}. \quad (2.50)$$

We can verify  $\pi_c(m_c) > \pi_c(m_w)$  and  $\pi_w(m_w) > \pi_w(m_c)$  when  $\hat{p} \in [\frac{\hat{A}(1-\gamma^2)\eta^2}{N}, \frac{A(1-\gamma^2)}{N})$ . The upper bound  $\frac{A(1-\gamma^2)}{N}$  is determined when water quality landowners start to sell in the carbon market so that  $\hat{p} < \frac{p_w}{\eta} = \frac{\hat{A}(1-\gamma^2)\eta}{N\eta}$ .

When the carbon price  $\hat{p} \in [\frac{A(1-\gamma^2)}{N}, \hat{A}(1-\gamma^2))$ , all carbon landowners will choose to sell in the carbon market and some water quality landowners will choose to sell in the water quality market. In this situation, the market clearing condition is,

$$\tau_2 Nw_w^{SM}(m_w) = \hat{A}, \quad (2.51)$$

and

$$p_w = \frac{\hat{A}(1-\gamma^2)\eta}{\tau_2 N}. \quad (2.52)$$

In this situation,  $\tau_2 N$  water quality landowners will choose to sell in the water quality market and all carbon landowners will choose to sell in the carbon market with



$\tau_2 = \frac{\hat{A}(1-\gamma^2)}{\hat{p}N}$ . When  $\hat{p} \geq \hat{A}(1-\gamma^2)$ , the last water quality landowner moves out of the water quality market since  $\hat{p} \geq \frac{p_w}{\eta}$ .

Define  $\hat{p}_1 \equiv \frac{\hat{A}(1-\gamma^2)\eta^2}{N(1+\eta^2)}$ ,  $\hat{p}_2 \equiv \frac{\hat{A}\eta^2(1-\gamma^2)}{N}$ ,  $\hat{p}_3 \equiv \frac{\hat{A}(1-\gamma^2)}{N}$  and  $\hat{p}_4 \equiv \hat{A}(1-\gamma^2)$ . Since  $\gamma, \eta \in (0, 1)$ , we can infer that  $\hat{p}_1 < \hat{p}_2 < \hat{p}_3 < \hat{p}_4$ . If  $\hat{p} \leq \hat{p}_1$ , then the market participation choices are  $(m_w, m_w)$ ; if  $\hat{p} \in [\hat{p}_1, \hat{p}_2)$ , the market participation choices are  $(\tau_1 m_w, m_w)$ , where  $\tau_1 = \frac{\hat{A}(1-\gamma^2)}{\hat{p}N} - \frac{1}{\eta^2}$ ; if  $\hat{p} \in [\hat{p}_2, \hat{p}_3)$ , the market participation choices are  $(m_c, m_w)$ ; if  $\hat{p} \in [\hat{p}_3, \hat{p}_4)$ , the market participation choices are  $(m_c, (1-\tau_2)m_c)$ , where  $\tau_2 = \frac{\hat{A}(1-\gamma^2)}{\hat{p}N}$ ; if  $\hat{p} \geq \hat{p}_4$ , the equilibrium market participation choices are  $(m_c, m_c)$ .

**Proof for Proposition 2.3** The carbon credits produced in MM

$$\begin{aligned}
Q_c^{MM} &= N \left( \frac{\frac{\hat{p}}{\eta} + p_w \gamma}{1-\gamma^2} + \frac{\eta \hat{p} + \gamma p_w}{1-\gamma^2} \right) \\
&= N \left( \hat{p} \left( \frac{1}{\eta(1-\gamma^2)} + \frac{\gamma}{1-\gamma^2} \right) + 2p_w \frac{\gamma}{1-\gamma^2} \right) \\
&= N \left( \hat{p} \left( \frac{1}{\eta(1-\gamma^2)} + \frac{\gamma}{1-\gamma^2} \right) - \frac{4\hat{p}\gamma^2}{(1-\gamma^2)(\eta + \frac{1}{\eta})} + \frac{2\hat{A}\gamma}{\eta + \frac{1}{\eta}} \right) \\
&= N \left( \hat{p} \frac{1+\eta^2}{\eta(1-\gamma^2)} + 2\gamma \left( \hat{A} - \frac{2\hat{p}\gamma}{1-\gamma^2} \right) \frac{\eta}{1+\eta^2} \right)
\end{aligned} \tag{2.53}$$

since

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

according to equation (2.10) when  $p_w > 0$ . Therefore, accounting the situation when  $\hat{p} \geq \tilde{p}$  with  $\tilde{p} = \frac{\hat{A}(1-\gamma^2)}{2N\gamma}$ , we can conclude that

$$Q_c^{MM} = N\hat{p} \frac{1+\eta^2}{\eta(1-\gamma^2)} + N * \max \left( 2\gamma \left( \hat{A} - \frac{2\hat{p}\gamma}{1-\gamma^2} \right) \frac{\eta}{1+\eta^2}, 0 \right), \tag{2.54}$$

Take the partial derivative of  $Q_c^{MM}$  w.r.t.  $\hat{A}$ , we have

$$\frac{\partial Q_c^{MM}}{\partial \hat{A}} = N * \max\left(\frac{2\gamma\eta}{1+\eta^2}, 0\right) \geq 0. \quad (2.55)$$

Take the partial derivative of  $Q_c^{MM}$  w.r.t.  $\hat{p}$ , we have

$$\begin{aligned} \frac{\partial Q_c^{MM}}{\partial \hat{p}} &= N \left( \frac{1+\eta^2}{\eta(1-\gamma^2)} - \frac{4\gamma^2}{1-\gamma^2} \frac{\eta}{1+\eta^2} \right) \\ &= N \left( \frac{1}{1-\gamma^2} \left( \frac{1+\eta^2}{\eta} - 4\gamma^2 \frac{\eta}{1+\eta^2} \right) \right) \\ &> N \left( \frac{1}{1-\gamma^2} \left( \frac{2\eta}{\eta} - 4\gamma^2 \frac{\eta}{2\eta} \right) \right) \\ &= N \left( \frac{1}{1-\gamma^2} (2 - 2\gamma^2) \right) \\ &> 0 \end{aligned} \quad (2.56)$$

when  $\hat{p} < \tilde{p}$ . When  $p \geq \tilde{p}$ ,  $\frac{\partial Q_c^{MM}}{\partial \hat{p}} = N \frac{1+\eta^2}{\eta(1-\gamma^2)}$ . Since  $\gamma \in (0, 1)$  and  $\eta \in (0, 1)$ , we conclude  $\frac{\partial Q_c^{MM}}{\partial \hat{A}} \geq 0$  and  $\frac{\partial Q_c^{MM}}{\partial \hat{p}} \geq 0$ , with the equalities hold only when  $p \geq \tilde{p}$ .

**Proof for Proposition 2.4** To calculate the total credits produced in the SM institution, we need to consider different market participation choices in relevant carbon price ranges. According to Proposition 2.1, we can further infer that,

- $\hat{p} \leq \hat{p}_1$ ,<sup>7</sup> the landowners' participation choices are  $J_c = m_w, J_w = m_w$ , then  $Q_w(m_w, m_w) = \hat{A}$  and  $Q_c(m_w, m_w) = p_w(m_w, m_w) \frac{2N\gamma}{1-\gamma^2}$ ;
- $\hat{p} \in [\hat{p}_1, \hat{p}_2)$ , the landowners' participation choices are  $J_c = \tau_1 m_w, J_w = m_w$ , then  $Q_w(\tau_1 m_w, m_w) = \hat{A} + \frac{\tau_1 N \gamma \hat{p}}{1-\gamma^2}$  and  $Q_c(\tau_1 m_w, m_w) = N * \frac{(1-\tau_1)\hat{p}/\eta + (1+\tau_1)\gamma p_w(\tau_1 m_w, m_w)}{1-\gamma^2}$ ;
- $\hat{p} \in [\hat{p}_2, \hat{p}_3)$ , the landowners' participation choices are  $J_c = m_c, J_w = m_w$  then

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<sup>7</sup>The prices  $\hat{p}_1, \hat{p}_2, \hat{p}_3$  and  $\hat{p}_4$  are defined in Propostion 2.1

$$Q_w(m_c, m_w) = \hat{A} + N * \frac{\gamma \hat{p}}{1 - \gamma^2} \text{ and } Q_c(m_c, m_w) = N * \frac{\hat{p}/\eta + \gamma p_w(m_c, m_w)}{1 - \gamma^2}.$$

- $\hat{p} \in [\hat{p}_3, \hat{p}_4)$ , the landowners' participation choices are  $J_c = m_c, J_w = (1 - \tau_2)m_c$ , which implies  $Q_w(m_c, (1 - \tau_2)m_c) = \hat{A} + \frac{N\gamma\hat{p}}{1 - \gamma^2} + \frac{(1 - \tau_2)N\gamma\hat{p}}{1 - \gamma^2}$  and  $Q_c(m_c, (1 - \tau_2)m_c) = \frac{N}{1 - \gamma^2}(\frac{\hat{p}}{\eta} + (1 - \tau_2)\hat{p}\eta + \tau_2\gamma p_w(m_c, (1 - \tau_2)m_c))$ ;
- $\hat{p} \geq \hat{p}_4$ , the landowners' participation choices are  $J_c = m_c, J_w = m_c, Q_w(m_c, m_c) = \hat{p}N \frac{2\gamma}{1 - \gamma^2}$  and  $Q_c(m_c, m_c) = \hat{p}N \frac{1/\eta + \eta}{1 - \gamma^2}$ ;

$$\text{where } p_w(m_c, m_w) = \frac{\hat{A}\eta(1 - \gamma^2)}{N}, p_w(m_w, m_w) = \frac{\hat{A}\eta(1 - \gamma^2)}{N(1 + \eta^2)}, p_w(m_w, m_c) = \frac{\hat{A}(1 - \gamma^2)}{N\eta},$$

$$p_w(\tau_1 m_w, m_w) = \frac{\hat{A}(1 - \gamma^2)}{N(\tau_1\eta + \frac{1}{\eta})}, \text{ and } p_w(m_c, (1 - \tau_2)m_c) = \frac{\hat{A}\eta(1 - \gamma^2)}{\tau_2 N}.$$

Comparing the total water quality credits produced, we find  $Q_w^{SM} \geq Q_w^{MM} = \hat{A}$  if  $\hat{p} < \hat{p}_4$ . When  $\hat{p} \geq \hat{p}_4$ , the carbon price is so high that both types decide to sell in the carbon market in the SM,  $Q_w^{SM} = Q_w^{MM} > \hat{A}$  if  $\hat{p} \geq \frac{\hat{A}(1 - \gamma^2)}{2N\gamma}$ . In the SM, when both types choose to sell in the carbon market ( $\hat{p} \geq \hat{p}_4$ ), the total carbon credits produced are the highest

$$Q_c(m_c, m_c) = N * \frac{\hat{p}/\eta + \hat{p}\eta}{1 - \gamma^2} = N\hat{p} \frac{1 + \eta^2}{\eta(1 - \gamma^2)}. \quad (2.57)$$

The total carbon credit produced in the MM is:

$$Q_c^{MM} = \hat{p}N \frac{1 + \eta^2}{\eta(1 - \gamma^2)} + \max\left(2\gamma(\hat{A} - \frac{2\hat{p}N\gamma}{1 - \gamma^2}) \frac{\eta}{1 + \eta^2}, 0\right), \quad (2.58)$$

since the water quality price  $p_w$  in the MM cannot fall below zero.

Therefore,  $Q_c^{MM} \geq Q_c^{SM}$ .

## Proof for Proposition 2.5

**Optimal Cap Choice in MM** In the MM institution where credit stacking is allowed, when  $\hat{p} < \frac{A_r(1-\gamma^2)}{2N\gamma}$ ,  $Q_w(A_r) = A_r$ ; when  $\hat{p} \geq \frac{A_r(1-\gamma^2)}{2N\gamma}$ ,  $Q_w(A_r) = \frac{2\hat{p}N\gamma}{1-\gamma^2}$ . Thus,  $Q'_w(A_r) = 0$ . Substitute the marginal benefit functions, the LHS of equation (2.20) becomes,

$$B'_c(Q_c(A_r)) Q'_c(A_r) + B'_w(Q_w(A_r)) Q'_w(A_r) = d_c \left( \sum_{i=1}^N \frac{\partial c_i(A_r)}{\partial A_r} + \sum_{k=1}^N \frac{\partial c_k(A_r)}{\partial A_r} \right) + d_w. \quad (2.59)$$

In the MM, since there is no restriction on the market participation choices,  $\hat{p} = \frac{\partial g_{ci}(\cdot)}{\partial c_i} = \frac{\partial g_{wk}(\cdot)}{\partial c_k}$  and  $p_w(A_r) = \frac{\partial g_{ci}(\cdot)}{\partial w_i} = \frac{\partial g_{wk}(\cdot)}{\partial w_k}$  for any carbon landowner  $i$  and water quality landowner  $k$ . Also, according to the supply functions (2.7) and (2.8) in MM, we have,  $\frac{\partial c_i(A_r)}{\partial A_r} = \frac{\gamma}{N(\eta + \frac{1}{\eta})}$ ,  $\frac{\partial w_i(A_r)}{\partial A_r} = \frac{\eta}{N(\eta + \frac{1}{\eta})}$ ,  $\frac{\partial c_k(A_r)}{\partial A_r} = \frac{\gamma}{N(\eta + \frac{1}{\eta})}$  and  $\frac{\partial w_k(A_r)}{\partial A_r} = \frac{1}{N\eta(\eta + \frac{1}{\eta})}$ . As a result, the RHS of equation (2.20) becomes,

$$\begin{aligned} & N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_r)}{\partial A_r} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_r)}{\partial A_r} \right) + N \left( \frac{\partial g_{wk}}{\partial c_k} \frac{\partial c_k(A_r)}{\partial A_r} + \frac{\partial g_{wk}}{\partial w_k} \frac{\partial w_k(A_r)}{\partial A_r} \right) \\ &= \frac{2\hat{p}\gamma}{\eta + \frac{1}{\eta}} + p_w(A_r). \end{aligned} \quad (2.60)$$

Therefore,

$$\frac{2\hat{p}\gamma}{\eta + \frac{1}{\eta}} + d_w = \frac{2\hat{p}\gamma}{\eta + \frac{1}{\eta}} + p_w(A_r), \quad (2.61)$$

or

$$d_w = p_w(A_r). \quad (2.62)$$

Therefore, in the MM, the marginal benefit of water quality improvement equals the equilibrium price in the water quality market. The optimal cap choice in MM

$$A_r^{MM} = \frac{d_w(\eta + \frac{1}{\eta}) + 2\gamma\hat{p}}{1 - \gamma^2} N, \quad (2.63)$$

and the society achieves its first best outcome. The maximized social net benefit is

$$NB_r^{MM} = \frac{\frac{1}{2}(\hat{p}^2 + d_w^2)(\frac{1}{\eta} + \eta) + 2\hat{p}d_w\gamma}{1 - \gamma^2}N \quad (2.64)$$

**Optimal Cap Choice in SM** In the SM institution where credit stacking is not allowed, landowners' could only choose to participate and receive revenue from one market. According to Propostion 2.1, depending on the carbon credit price  $\hat{p}$ , landowners' participation choices would differ. Therefore, for a given carbon price  $\hat{p}$ , a regulator could choose a cap  $A_r$  so that different market participation choices might emerge.

Specifically, when  $A_r \geq \frac{(1+\eta^2)\hat{p}N}{(1-\gamma^2)\eta^2}$ , the equilibrium market participation choices are  $(m_w, m_w)$ . Thus, the LHS of equation (2.20) becomes,

$$B'_c(Q_c(A_r))Q'_c(A_r) + B'_w(Q_w(A_r))Q'_w(A_r) = d_c \left( \sum_{i=1}^N \frac{\partial c_i(A_r)}{\partial A_r} + \sum_{k=1}^N \frac{\partial c_k(A_r)}{\partial A_r} \right) + d_w. \quad (2.65)$$

Due to the SM restriction, only  $p_w(A_r) = \frac{\partial g_{ci}(\cdot)}{\partial w_i} = \frac{\partial g_{wk}(\cdot)}{\partial w_k}$  holds for any carbon landowner  $i$  and water quality landowner  $k$ . Also, according to the supply functions in SM, we have,  $\frac{\partial c_i(A_r)}{\partial A_r} = \frac{\gamma}{N(\eta + \frac{1}{\eta})}$ ,  $\frac{\partial w_i(A_r)}{\partial A_r} = \frac{\eta}{N(\eta + \frac{1}{\eta})}$ ,  $\frac{\partial c_k(A_r)}{\partial A_r} = \frac{\gamma}{N(\eta + \frac{1}{\eta})}$  and  $\frac{\partial w_k(A_r)}{\partial A_r} = \frac{1}{N\eta(\eta + \frac{1}{\eta})}$ . As a result, the RHS of equation (2.20) becomes,

$$\begin{aligned} & N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_r)}{\partial A_r} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_r)}{\partial A_r} \right) + N \left( \frac{\partial g_{wk}}{\partial c_k} \frac{\partial c_k(A_r)}{\partial A_r} + \frac{\partial g_{wk}}{\partial w_k} \frac{\partial w_k(A_r)}{\partial A_r} \right) \\ &= \frac{\gamma}{\eta + \frac{1}{\eta}} \left( \frac{\partial g_{ci}}{\partial c_i} + \frac{\partial g_{ci}}{\partial w_i} \right) + p_w(A_r) \\ &= \frac{\gamma}{\eta + \frac{1}{\eta}} \left( \frac{\eta\gamma p_w(A_r)}{1-\gamma^2} - \frac{\gamma p_w(A_r)\eta}{1-\gamma^2} + \frac{\gamma p_w(A_r)}{\eta(1-\gamma^2)} - \frac{\gamma p_w(A_r)}{\eta(1-\gamma^2)} \right) + p_w(A_r) \\ &= p_w(A_r) \end{aligned} \quad (2.66)$$

Therefore,

$$\frac{2\hat{p}\gamma}{\eta + \frac{1}{\eta}} + d_w = p_w(A_r), \quad (2.67)$$

or

$$d_w = p_w(A_r) - \frac{2\hat{p}\gamma}{\eta + \frac{1}{\eta}}. \quad (2.68)$$

Substitute in the equilibrium market price  $p_w(A_r) = \frac{A_r(1-\gamma^2)}{N(\frac{1}{\eta}+\eta)}$ , we can find that the optimal cap choice in SM when

$$A_r \geq \frac{(1+\eta^2)\hat{p}N}{(1-\gamma^2)\eta^2}$$

is

$$A_r^{SM} = \frac{d_w(\eta + \frac{1}{\eta}) + 2\gamma\hat{p}}{1 - \gamma^2}N. \quad (2.69)$$

When  $A_r \in [\frac{\hat{p}(N+\eta^2)}{(1-\gamma^2)\eta^2}, \frac{\hat{p}N(1+\eta^2)}{(1-\gamma^2)\eta^2})$ , the equilibrium market participation choices are  $(\tau_1 m_w, m_w)$ , which implies  $(1-\tau_1)N$  carbon landowners will choose the carbon market while the others,  $\tau_1 N$  carbon landowners and  $N$  water quality landowners, will choose the water quality market. Due to the SM restriction, only  $p_w(A_r) = \frac{\partial g_{ci}(\cdot)}{\partial w_i} = \frac{\partial g_{wk}(\cdot)}{\partial w_k}$  hold for any carbon landowner  $i$  and water quality landowner  $k$ . Also, according to the supply functions in SM, we have,  $\frac{\partial c_i(A_r)}{\partial A_r} = \frac{\gamma}{N(\tau_1\eta + \frac{1}{\eta})}$ ,  $\frac{\partial w_i(A_r)}{\partial A_r} = \frac{\eta}{N(\tau_1\eta + \frac{1}{\eta})}$ ,  $\frac{\partial c_k(A_r)}{\partial A_r} = \frac{\gamma}{N(\tau_1\eta + \frac{1}{\eta})}$  and  $\frac{\partial w_k(A_r)}{\partial A_r} = \frac{1}{N\eta(\tau_1\eta + \frac{1}{\eta})}$  when a landowner chooses the water quality market ( $j = m_w$ ), and  $\frac{\partial c_i(A_r)}{\partial A_r} = \frac{\partial w_i(A_r)}{\partial A_r} = \frac{\partial c_k(A_r)}{\partial A_r} = \frac{\partial w_k(A_r)}{\partial A_r} = 0$  when a landowner chooses

the carbon market ( $j = m_c$ ). As a result, the RHS of equation (2.20) becomes,

$$\begin{aligned}
& (1 - \tau_1(A_r))N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_r)}{\partial A_r} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_r)}{\partial A_r} \right) + \tau_1(A_r)N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_r)}{\partial A_r} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_r)}{\partial A_r} \right) \\
& + (\tau'_1(A_r) - \tau_1'(A_r))N g_{ci}(c_i, w_i) + \sum_{k=1}^N \left( \frac{\partial g_{wk}}{\partial c_k} \frac{\partial c_k(A_r)}{\partial A_r} + \frac{\partial g_{wk}}{\partial w_k} \frac{\partial w_k(A_r)}{\partial A_r} \right) \\
& = \frac{\gamma}{\eta + \frac{1}{\eta}} (\tau_1 \frac{\partial g_{ci}}{\partial c_i} + \frac{\partial g_{ci}}{\partial w_i}) + p_w(A_r) \\
& = \frac{\gamma}{\eta + \frac{1}{\eta}} \left( \tau_1 \left( \frac{\eta \gamma p_w(A_r)}{1 - \gamma^2} - \frac{\gamma p_w(A_r) \eta}{1 - \gamma^2} \right) + \frac{\gamma p_w(A_r)}{\eta(1 - \gamma^2)} - \frac{\gamma p_w(A_r)}{\eta(1 - \gamma^2)} \right) + p_w(A_r) \\
& = p_w(A_r) = \frac{\hat{p}}{\eta}
\end{aligned} \tag{2.70}$$

Therefore,

$$\frac{\hat{p}(\gamma - 1)}{\eta} + d_w = p_w(A_r) = \frac{\hat{p}}{\eta}, \tag{2.71}$$

or

$$d_w = \hat{p} \left( \frac{2}{\eta} - \frac{\gamma}{\eta} \right). \tag{2.72}$$

When  $A_r \in [\frac{N\hat{p}}{1-\gamma^2}, \frac{\hat{p}(N+\eta^2)}{(1-\gamma^2)\eta^2})$  and the equilibrium market participation choices are  $(m_c^*, m_w^*)$ . Due to the SM restriction, only  $p_w(A_r) = \frac{\partial g_{wk}(\cdot)}{\partial w_k}$  and  $\hat{p} = \frac{\partial g_{ci}(\cdot)}{\partial c_i}$  hold for any carbon landowner  $i$  and water quality landowner  $k$ . Also, according to the supply functions in SM, we have,  $\frac{\partial c_i(A_r)}{\partial A_r} = \frac{\partial w_i(A_r)}{\partial A_r} = 0$ ,  $\frac{\partial c_k(A_r)}{\partial A_r} = \frac{\gamma}{N(\eta + \frac{1}{\eta})}$  and  $\frac{\partial w_k(A_r)}{\partial A_r} = \frac{1}{N\eta(\eta + \frac{1}{\eta})}$ . As a result, the RHS of equation (2.20) becomes,

$$\begin{aligned}
& N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_r)}{\partial A_r} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_r)}{\partial A_r} \right) + N \left( \frac{\partial g_{wk}}{\partial c_k} \frac{\partial c_k(A_r)}{\partial A_r} + \frac{\partial g_{wk}}{\partial w_k} \frac{\partial w_k(A_r)}{\partial A_r} \right) \\
& = p_w(A_r)
\end{aligned} \tag{2.73}$$

Therefore,

$$\frac{\hat{p}\gamma}{\frac{1}{\eta}} + d_w = p_w(A_r), \tag{2.74}$$

or

$$d_w = p_w(A_r) - \hat{p}\gamma\eta. \quad (2.75)$$

Substitute in the equilibrium market price  $p_w(A_r) = \frac{A_r(1-\gamma^2)}{N^{\frac{1}{\eta}}}$ , we can find that the optimal cap choice in SM is

$$A_r^{SM} = \frac{d_w^{\frac{1}{\eta}} + \gamma\hat{p}}{1 - \gamma^2} N. \quad (2.76)$$

When  $A_r \in [\frac{\hat{p}}{1-\gamma^2}, \frac{N\hat{p}}{1-\gamma^2})$ , the equilibrium market participation choices are  $(m_c, (1 - \tau_2)m_c)$ , which means  $\tau_2 N$  water quality landowners will choose the water quality market while the others, including  $(1 - \tau_2)N$  water quality landowners and  $N$  carbon landowners, will choose the carbon market. Due to the SM restriction, only  $p_w(A_r) = \frac{\partial g_{wk}(\cdot)}{\partial w_k}$  holds for water quality landowner  $k$  choose to sell in the water quality market. Also, according to the supply functions in SM, we have,  $\frac{\partial c_k(A_r)}{\partial A_r} = \frac{\gamma}{N\tau_2^{\frac{1}{\eta}}}$  and  $\frac{\partial w_k(A_r)}{\partial A_r} = \frac{1}{N\eta\tau_2^{\frac{1}{\eta}}}$  when a landowner chooses the water quality market ( $j = m_w$ ), and  $\frac{\partial c_i(A_r)}{\partial A_r} = \frac{\partial w_i(A_r)}{\partial A_r} = \frac{\partial c_k(A_r)}{\partial A_r} = \frac{\partial w_k(A_r)}{\partial A_r} = 0$  when a landowner chooses the carbon market ( $j = m_c$ ). As a result, the RHS of equation (2.20) becomes,

$$\begin{aligned} & N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_r)}{\partial A_r} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_r)}{\partial A_r} \right) + \tau_2(A_r) N \left( \frac{\partial g_{ck}}{\partial c_k} \frac{\partial c_k(A_r)}{\partial A_r} + \frac{\partial g_{ck}}{\partial w_k} \frac{\partial w_k(A_r)}{\partial A_r} \right) \\ & + (1 - \tau_2(A_r)) N \left( \frac{\partial g_{wk}}{\partial c_k} \frac{\partial c_k(A_r)}{\partial A_r} + \frac{\partial g_{wk}}{\partial w_k} \frac{\partial w_k(A_r)}{\partial A_r} \right) + N(\tau_2'(A_r) - \tau_2'(A_r)) g_{wk}(c_k, w_k) \\ & = p_w(A_r) = \hat{p}\eta \end{aligned} \quad (2.77)$$

Therefore,

$$\left( \frac{\gamma}{\eta} - \eta \right) \hat{p} + d_w = p_w(A_r) = \hat{p}\eta, \quad (2.78)$$

or

$$d_w = \hat{p} \left( 2\eta - \frac{\gamma}{\eta} \right). \quad (2.79)$$



When  $A_r < \frac{\hat{p}}{1-\gamma^2}$ , the equilibrium market participation choices are  $(m_c, m_c)$ , all landowners will choose the carbon market. Since  $\frac{\partial c_i(A_r)}{\partial A_r} = \frac{\partial w_i(A_r)}{\partial A_r} = \frac{\partial c_k(A_r)}{\partial A_r} = \frac{\partial w_k(A_r)}{\partial A_r} = 0$  when a landowner chooses the carbon market ( $j = m_c$ ). As a result, the RHS of equation (2.20) becomes,

$$\begin{aligned} & N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_r)}{\partial A_r} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_r)}{\partial A_r} \right) + N \left( \frac{\partial g_{ck}}{\partial c_k} \frac{\partial c_k(A_r)}{\partial A_r} + \frac{\partial g_{ck}}{\partial w_k} \frac{\partial w_k(A_r)}{\partial A_r} \right) \\ &= 0 \end{aligned} \quad (2.80)$$

and the LHS of equation (2.20) also equals 0. Therefore, the choice of the regulator cap  $A_r$  does not matter as long as  $A_r < \frac{\hat{p}}{1-\gamma^2}$ .

To summarize, when  $d_w > \hat{p}(\frac{2}{\eta} - \frac{\gamma}{\eta})$ , the regulator chooses the cap  $A_r = \frac{d_w(\eta + \frac{1}{\eta}) + 2\gamma\hat{p}}{1-\gamma^2}N$ ; when  $d_w = \hat{p}(\frac{2}{\eta} - \frac{\gamma}{\eta})$ , the regulator could choose any cap  $A_r \in \left( \frac{(N+\eta^2)\hat{p}}{(1-\gamma^2)\eta^2}, \frac{N(1+\eta^2)\hat{p}}{(1-\gamma^2)\eta^2} \right)$ ; when  $d_w \in (\hat{p}(2\eta - \frac{\gamma}{\eta}), \hat{p}(\frac{2}{\eta} - \frac{\gamma}{\eta}))$ , the regulator chooses the cap  $A_r = \frac{d_w\frac{1}{\eta} + \gamma\hat{p}}{1-\gamma^2}N$ ; when  $d_w = \hat{p}(2\eta - \frac{\gamma}{\eta})$ , the regulator could choose any cap  $A_r \in \left( \frac{\hat{p}}{1-\gamma^2}, \frac{N\hat{p}}{1-\gamma^2} \right)$ ; when  $d_w < \hat{p}(2\eta - \frac{\gamma}{\eta})$ , the regulator could choose any cap  $A_r \leq \frac{\hat{p}}{1-\gamma^2}$ .<sup>8</sup>

**Proof for Proposition 2.6** The Proposition 2.6 could come directly from the “second-best” theory as the MM always achieve the social optimal outcome while the restriction in SM could only lead a weakly smaller social net benefit. To see this, when the social planner cares about both the carbon sequestration and water quality benefit, the social net benefit in MM is

$$NB_r^{MM} = \frac{\frac{1}{2}(\hat{p}^2 + d_w^2)(\frac{1}{\eta} + \eta)}{1 - \gamma^2}N + \frac{2\hat{p}d_w\gamma}{1 - \gamma^2}N. \quad (2.81)$$

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<sup>8</sup>We are assuming the more general case where  $2\eta - \frac{\gamma}{\eta} > 0$ ; when  $2\eta - \frac{\gamma}{\eta} \leq 0$ , we don't have the latter two cases.

When  $p < \frac{d_w \eta}{2 - \gamma}$ , the social net benefit in SM is,

$$NB_r^{SM} = \frac{p_w(d_w - \frac{p_w}{2})(\frac{1}{\eta} + \eta)}{1 - \gamma^2}N + \frac{2\hat{p}p_w\gamma}{1 - \gamma^2}N. \quad (2.82)$$

Thus,

$$\Delta NB_1 = NB_r^{MM} - NB_r^{SM} = \frac{N\hat{p}^2(1 + 2(1 - 2\gamma^2)\eta^2 + \eta^4)}{2\eta(1 + \eta^2)(1 - \gamma^2)} > \frac{N\hat{p}^2(1 - 2\eta^2 + \eta^4)}{2\eta(1 + \eta^2)(1 - \gamma^2)} \geq 0. \quad (2.83)$$

When  $p \in [\frac{d_w \eta}{2 - \gamma}, \frac{d_w \eta}{2\eta^2 - \gamma})$ , the social net benefit in SM is,

$$NB_r^{SM} = \frac{\frac{\hat{p}^2}{2} + p_w(d_w - \frac{p_w}{2})}{(1 - \gamma^2)\eta}N + \frac{\hat{p}(p_w + d_w)\gamma}{1 - \gamma^2}N. \quad (2.84)$$

Thus,

$$\Delta NB_2 = NB_r^{MM} - NB_r^{SM} = \frac{\eta N(d_w^2 + \hat{p}(1 - \gamma^2))}{2(1 - \gamma^2)} > 0. \quad (2.85)$$

When  $p > \frac{d_w \eta}{2\eta^2 - \gamma}$ , the social net benefit in SM is,

$$NB_r^{SM} = \frac{\frac{1}{2}\hat{p}^2(\frac{1}{\eta} + \eta)}{1 - \gamma^2}N + \frac{2\hat{p}d_w\gamma}{1 - \gamma^2}N. \quad (2.86)$$

Thus,

$$\Delta NB_3 = NB_r^{MM} - NB_r^{SM} = \frac{d_w^2 N(1 + \eta^2)}{2\eta(1 - \gamma^2)} > 0. \quad (2.87)$$

Therefore, the SM leads to a lower net social benefit compared to MM, which maximizes the net social benefit when the regulator considers both carbon sequestration and water quality improvement benefit and chooses the cap optimally.

### Proof for Proposition 2.7

**Second-Best Cap Choice in MM** When the regulator cares only about the water quality improvement benefit, the LHS of equation (2.25) becomes,

$$B'_w(Q_w(A_{r'})) Q'_w(A_{r'}) = d_w. \quad (2.88)$$

In the MM, since there is not restrictions on the market participation choices,  $\hat{p} = \frac{\partial g_{ci}(\cdot)}{\partial c_i} = \frac{\partial g_{wk}(\cdot)}{\partial c_k}$  and  $p_w(A_{r'}) = \frac{\partial g_{ci}(\cdot)}{\partial w_i} = \frac{\partial g_{wk}(\cdot)}{\partial w_k}$  for any carbon landowner  $i$  and water quality landowner  $k$ . Also, according to the supply functions (2.7) and (2.8) in MM, we have,  $\frac{\partial c_i(A_{r'})}{\partial A_{r'}} = \frac{\gamma}{N(\eta + \frac{1}{\eta})}$ ,  $\frac{\partial w_i(A_{r'})}{\partial A_{r'}} = \frac{\eta}{N(\eta + \frac{1}{\eta})}$ ,  $\frac{\partial c_k(A_{r'})}{\partial A_{r'}} = \frac{\gamma}{N(\eta + \frac{1}{\eta})}$  and  $\frac{\partial w_k(A_{r'})}{\partial A_{r'}} = \frac{1}{N\eta(\eta + \frac{1}{\eta})}$ . As a result, the RHS of equation (2.25) becomes,

$$\begin{aligned} & \sum_{i=1}^N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_{r'})}{\partial A_{r'}} \right) + \sum_{k=1}^N \left( \frac{\partial g_{wk}}{\partial c_k} \frac{\partial c_k(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{wk}}{\partial w_k} \frac{\partial w_k(A_{r'})}{\partial A_{r'}} \right) \\ &= \frac{2\hat{p}\gamma}{\eta + \frac{1}{\eta}} + p_w(A_{r'}). \end{aligned} \quad (2.89)$$

As a result,<sup>9</sup>

$$d_w = p_w(A_{r'}) + \frac{2\hat{p}\gamma}{\eta + \frac{1}{\eta}}. \quad (2.90)$$

Therefore, in the MM, the marginal benefit of water quality improvement equals the equilibrium price in the water quality market. The optimal cap choice in MM

$$A_{r'}^{MM} = \frac{d_w(\eta + \frac{1}{\eta})}{1 - \gamma^2} N, \quad (2.91)$$

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<sup>9</sup>Assume the water quality improvement benefit  $d_w$  is sufficiently large so that  $p_w(A_{r'}) > 0$ , or  $\hat{p} < \frac{d_w(1+\eta^2)}{2\eta\gamma}$ .

and the society achieves a second-second outcome. Note that the failure to recognize the carbon benefit leads to a lower water quality trading cap in the MM since  $A_{r'}^{MM} < A_r^{MM}$ .

**Second-Best Cap Choice in SM** In the SM institution where credit stacking is not allowed, landowners' could only choose to participate and receive revenue from one market. According to Propostion 2.1, depending on the carbon credit price  $\hat{p}$ , landowners' participation choices might differ.

Specifically, when  $A_r \geq \frac{(1+\eta^2)\hat{p}N}{(1-\gamma^2)\eta^2}$ , the equilibrium market participation choices are  $(m_w, m_w)$ . Thus, the LHS of equation (2.25) becomes,

$$B'_w(Q_w(A_{r'}))Q'_w(A_{r'}) = d_w. \quad (2.92)$$

Due to the SM restriction, only  $p_w(A_{r'}) = \frac{\partial g_{ci}(\cdot)}{\partial w_i} = \frac{\partial g_{wk}(\cdot)}{\partial w_k}$  hold for any carbon landowner  $i$  and water quality landowner  $k$ . Also, according to the supply functions in SM, we have,  $\frac{\partial c_i(A_{r'})}{\partial A_{r'}} = \frac{\gamma}{N(\eta+\frac{1}{\eta})}$ ,  $\frac{\partial w_i(A_{r'})}{\partial A_{r'}} = \frac{\eta}{N(\eta+\frac{1}{\eta})}$ ,  $\frac{\partial c_k(A_{r'})}{\partial A_{r'}} = \frac{\gamma}{N(\eta+\frac{1}{\eta})}$  and  $\frac{\partial w_k(A_{r'})}{\partial A_{r'}} = \frac{1}{N\eta(\eta+\frac{1}{\eta})}$ . As a result, the RHS of equation (2.25) becomes,

$$\begin{aligned} & N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_{r'})}{\partial A_{r'}} \right) + N \left( \frac{\partial g_{wk}}{\partial c_k} \frac{\partial c_k(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{wk}}{\partial w_k} \frac{\partial w_k(A_{r'})}{\partial A_{r'}} \right) \\ &= \frac{\gamma}{\eta+\frac{1}{\eta}} \left( \frac{\partial g_{ci}}{\partial c_i} + \frac{\partial g_{ci}}{\partial w_i} \right) + p_w(A_{r'}) \\ &= \frac{\gamma}{\eta+\frac{1}{\eta}} \left( \frac{\eta\gamma p_w(A_{r'})}{1-\gamma^2} - \frac{\gamma p_w(A_{r'})\eta}{1-\gamma^2} + \frac{\gamma p_w(A_{r'})}{\eta(1-\gamma^2)} - \frac{\gamma p_w(A_{r'})}{\eta(1-\gamma^2)} \right) + p_w(A_{r'}) \\ &= p_w(A_{r'}) \end{aligned} \quad (2.93)$$

Therefore,

$$d_w = p_w(A_{r'}), \quad (2.94)$$

We can find that the optimal cap choice in SM in this situation is

$$A_{r'}^{SM} = \frac{d_w(\eta + \frac{1}{\eta})}{1 - \gamma^2} N, \quad (2.95)$$

When  $A_{r'} \in [\frac{\hat{p}(N+\eta^2)}{(1-\gamma^2)\eta^2}, \frac{\hat{p}N(1+\eta^2)}{(1-\gamma^2)\eta^2})$ , the equilibrium market participation choices are  $(\tau_1 m_w^*, m_w^*)$ , which means  $(1 - \tau_1)N$  carbon landowners will choose the carbon market while the others,  $\tau_1 N$  carbon landowners and  $N$  water quality landowners, will choose the water quality market. Due to the SM restriction, only  $p_w(A_{r'}) = \frac{\partial g_{ci}(\cdot)}{\partial w_i} = \frac{\partial g_{wk}(\cdot)}{\partial w_k}$  hold for any carbon landowner  $i$  and water quality landowner  $k$ . Also, according to the supply functions in SM, we have,  $\frac{\partial c_i(A_{r'})}{\partial A_{r'}} = \frac{\gamma}{N(\tau_1 \eta + \frac{1}{\eta})}$ ,  $\frac{\partial w_i(A_{r'})}{\partial A_{r'}} = \frac{\eta}{N(\tau_1 \eta + \frac{1}{\eta})}$ ,  $\frac{\partial c_k(A_{r'})}{\partial A_{r'}} = \frac{\gamma}{N(\tau_1 \eta + \frac{1}{\eta})}$  and  $\frac{\partial w_k(A_{r'})}{\partial A_{r'}} = \frac{1}{N\eta(\tau_1 \eta + \frac{1}{\eta})}$  when a landowner chooses the water quality market ( $j = m_w$ ), and  $\frac{\partial c_i(A_{r'})}{\partial A_{r'}} = \frac{\partial w_i(A_{r'})}{\partial A_{r'}} = \frac{\partial c_k(A_{r'})}{\partial A_{r'}} = \frac{\partial w_k(A_{r'})}{\partial A_{r'}} = 0$  when a landowner chooses the carbon market ( $j = m_c$ ). As a result, the RHS of equation (2.25) becomes,

$$\begin{aligned} & (1 - \tau_1(A_{r'}))N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_{r'})}{\partial A_{r'}} \right) + \tau_1(A_{r'})N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_{r'})}{\partial A_{r'}} \right) \\ & + (\tau_1'(A_{r'}) - \tau_1(A_{r'}))N g_{ci}(c_i, w_i) + \sum_{k=1}^N \left( \frac{\partial g_{wk}}{\partial c_k} \frac{\partial c_k(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{wk}}{\partial w_k} \frac{\partial w_k(A_{r'})}{\partial A_{r'}} \right) \\ & = \frac{\gamma}{\eta + \frac{1}{\eta}} (\tau_1 \frac{\partial g_{ci}}{\partial c_i} + \frac{\partial g_{ci}}{\partial w_i}) + p_w(A_{r'}) \\ & = \frac{\gamma}{\eta + \frac{1}{\eta}} \left( \tau_1 \left( \frac{\eta \gamma p_w(A_{r'})}{1 - \gamma^2} - \frac{\gamma p_w(A_{r'}) \eta}{1 - \gamma^2} \right) + \frac{\gamma p_w(A_{r'})}{\eta(1 - \gamma^2)} - \frac{\gamma p_w(A_{r'})}{\eta(1 - \gamma^2)} \right) + p_w(A_{r'}) \\ & = p_w(A_{r'}) = \frac{\hat{p}}{\eta} \end{aligned} \quad (2.96)$$

Therefore,

$$d_w = p_w(A_{r'}) = \frac{\hat{p}}{\eta}, \quad (2.97)$$

When  $A_{r'} \in [\frac{N\hat{p}}{1-\gamma^2}, \frac{\hat{p}(N+\eta^2)}{(1-\gamma^2)\eta^2})$  and the equilibrium market participation choices are  $(m_c^*, m_w^*)$ . Due to the SM restriction, only  $p_w(A_{r'}) = \frac{\partial g_{wk}(\cdot)}{\partial w_k}$  and  $\hat{p} = \frac{\partial g_{ci}(\cdot)}{\partial c_i}$  hold

for any carbon landowner  $i$  and water quality landowner  $k$ . Also, according to the supply functions in SM, we have,  $\frac{\partial c_i(A_{r'})}{\partial A_{r'}} = \frac{\partial w_i(A_{r'})}{\partial A_{r'}} = 0$ ,  $\frac{\partial c_k(A_{r'})}{\partial A_{r'}} = \frac{\gamma}{N(\eta + \frac{1}{\eta})}$  and  $\frac{\partial w_k(A_{r'})}{\partial A_{r'}} = \frac{1}{N\eta(\eta + \frac{1}{\eta})}$ . As a result, the RHS of equation (2.25) becomes,

$$\begin{aligned} & N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_{r'})}{\partial A_{r'}} \right) + N \left( \frac{\partial g_{wk}}{\partial c_k} \frac{\partial c_k(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{wk}}{\partial w_k} \frac{\partial w_k(A_{r'})}{\partial A_{r'}} \right) \\ &= p_w(A_{r'}) \end{aligned} \quad (2.98)$$

Therefore,

$$d_w = p_w(A_{r'}), \quad (2.99)$$

Substitute in the equilibrium market price  $p_w(A_{r'}) = \frac{A_{r'}(1-\gamma^2)}{N\frac{1}{\eta}}$ , the optimal cap choice in SM is

$$A_{r'}^{SM} = \frac{d_w \frac{1}{\eta}}{1 - \gamma^2} N, \quad (2.100)$$

When  $A_{r'} \in [\frac{\hat{p}}{1-\gamma^2}, \frac{N\hat{p}}{1-\gamma^2})$ , the equilibrium market participation choices are  $(m_c, (1-\tau_2)m_c)$ , which means  $\tau_2 N$  water quality landowners will choose the water quality market while the others, including  $(1-\tau_2)N$  water quality landowners and  $N$  carbon landowners, will choose the carbon market. Due to the SM restriction, only  $p_w(A_{r'}) = \frac{\partial g_{wk}(\cdot)}{\partial w_k}$  holds for water quality landowner  $k$  who chooses to sell in the water quality market. Also, according to the supply functions in SM, we have,  $\frac{\partial c_k(A_{r'})}{\partial A_{r'}} = \frac{\gamma}{N\tau_2 \frac{1}{\eta}}$  and  $\frac{\partial w_k(A_{r'})}{\partial A_{r'}} = \frac{1}{N\eta\tau_2 \frac{1}{\eta}}$  when a landowner chooses the water quality market ( $j = m_w$ ), and  $\frac{\partial c_i(A_{r'})}{\partial A_{r'}} = \frac{\partial w_i(A_{r'})}{\partial A_{r'}} = \frac{\partial c_k(A_{r'})}{\partial A_{r'}} = \frac{\partial w_k(A_{r'})}{\partial A_{r'}} = 0$  when a landowner chooses the carbon

market ( $j = m_c$ ). As a result, the RHS of equation (2.25) becomes,

$$\begin{aligned}
& N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_{r'})}{\partial A_{r'}} \right) + \tau_2(A_{r'}) N \left( \frac{\partial g_{ck}}{\partial c_k} \frac{\partial c_k(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{ck}}{\partial w_k} \frac{\partial w_k(A_{r'})}{\partial A_{r'}} \right) \\
& + (1 - \tau_2(A_{r'})) N \left( \frac{\partial g_{wk}}{\partial c_k} \frac{\partial c_k(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{wk}}{\partial w_k} \frac{\partial w_k(A_{r'})}{\partial A_{r'}} \right) + N(\tau'_2(A_{r'}) - \tau'_2(A_{r'})) g_{wk}(c_k, w_k) \\
& = p_w(A_{r'}) = \hat{p}\eta
\end{aligned} \tag{2.101}$$

Therefore,

$$d_w = p_w(A_{r'}) = \hat{p}\eta, \tag{2.102}$$

When  $\hat{p} \geq \hat{p}_4$ , the equilibrium market participation choices are  $(m_c, m_c)$ , all landowners will choose the carbon market. Since  $\frac{\partial c_i(A_{r'})}{\partial A_{r'}} = \frac{\partial w_i(A_{r'})}{\partial A_{r'}} = \frac{\partial c_k(A_{r'})}{\partial A_{r'}} = \frac{\partial w_k(A_{r'})}{\partial A_{r'}} = 0$  when a landowner chooses the carbon market ( $j = m_c$ ). As a result, the RHS of equation (2.25) becomes,

$$\begin{aligned}
& N \left( \frac{\partial g_{ci}}{\partial c_i} \frac{\partial c_i(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{ci}}{\partial w_i} \frac{\partial w_i(A_{r'})}{\partial A_{r'}} \right) + N \left( \frac{\partial g_{ck}}{\partial c_k} \frac{\partial c_k(A_{r'})}{\partial A_{r'}} + \frac{\partial g_{ck}}{\partial w_k} \frac{\partial w_k(A_{r'})}{\partial A_{r'}} \right) \\
& = 0
\end{aligned} \tag{2.103}$$

Therefore, the choice of the regulator cap  $A_{r'}$  does not matter in this case. To summarize, when  $d_w > \frac{\hat{p}}{\eta}$ , the regulator chooses the cap  $A_{r'} = \frac{d_w(\eta + \frac{1}{\eta})}{1 - \gamma^2} N$ ; when  $d_w = \frac{\hat{p}}{\eta}$ , the regulator could choose any cap  $A_{r'} \in \left( \frac{(N + \eta^2)\hat{p}}{(1 - \gamma^2)\eta^2}, \frac{N(1 + \eta^2)\hat{p}}{(1 - \gamma^2)\eta^2} \right)$ ; when  $d_w \in (\hat{p}\eta, \frac{\hat{p}}{\eta})$ , the regulator chooses the cap  $A_{r'} = \frac{d_w \frac{1}{\eta}}{1 - \gamma^2} N$ ; when  $d_w = \hat{p}\eta$ , the regulator could choose any cap  $A_{r'} \in \left( \frac{\hat{p}}{1 - \gamma^2}, \frac{N\hat{p}}{1 - \gamma^2} \right)$ ; when  $d_w < \hat{p}\eta$ , the regulator could choose any cap  $A_{r'} \leq \frac{\hat{p}}{1 - \gamma^2}$ , for simplicity, assume  $A_{r'} = \frac{d_w}{(1 - \gamma^2)\eta}$ .

**Proof for Proposition 2.8** The maximal social net benefit from the first best benchmark is

$$NB_{max} = \frac{\frac{1}{2}(\hat{p}^2 + d_w^2)(\frac{1}{\eta} + \eta)}{1 - \gamma^2}N + \frac{2\hat{p}d_w\gamma}{1 - \gamma^2}N, \quad (2.104)$$

which equals to social net benefit in a MM when the regulator maximizes both carbon and water quality benefits and chooses the cap optimally.

When the regulator cares only about the water quality benefits, the social net benefit in MM is,

$$\begin{aligned} NB_{r'}^{MM} &= \frac{d_w^2(\frac{1}{\eta} + \eta)}{2(1 - \gamma^2)}N + \frac{\hat{p}^2(1 + \eta^4 + \eta^2(2 - 4\gamma^2))}{2(1 - \gamma^2)\eta(1 + \eta^2)}N + \frac{2\hat{p}d_w\gamma}{1 - \gamma^2}N \\ &< \frac{d_w^2(\frac{1}{\eta} + \eta)}{2(1 - \gamma^2)}N + \frac{\hat{p}^2(1 + \eta^2)^2}{2(1 - \gamma^2)\eta(1 + \eta^2)}N + \frac{2\hat{p}d_w\gamma}{1 - \gamma^2}N \\ &= NB_{max}. \end{aligned} \quad (2.105)$$

Therefore, when the social planner is only maximizing water quality benefit, the realized social benefit  $NB_{max}$  is always smaller compared to the situation when the social planner is maximizing both carbon and water quality benefit (i.e., the first-best benchmark). Note that if  $\gamma$  equals 0,  $NB_{max} = NB_{r'}^{MM}$  since there is no production complementarity.

When  $p \leq d_w\eta$ , the social net benefit in SM is,

$$NB_{r'}^{SM} = \frac{d_w^2(\frac{1}{\eta} + \eta)}{2(1 - \gamma^2)}N + \frac{2\hat{p}d_w\gamma}{1 - \gamma^2}N. \quad (2.106)$$

Thus,

$$\Delta NB'_1 = NB_r^{MM} - NB_r^{SM} = \frac{N\hat{p}^2(1 + 2(1 - 2\gamma^2)\eta^2 + \eta^4)}{2\eta(1 + \eta^2)(1 - \gamma^2)} \geq \frac{N\hat{p}^2(1 - 2\eta^2 + \eta^4)}{2\eta(1 + \eta^2)(1 - \gamma^2)} \geq 0. \quad (2.107)$$



When  $p \in (d_w\eta, \frac{d_w}{\eta}]$ , the social net benefit in SM is,

$$NB_r^{SM} = \frac{\hat{p}^2 + d_w^2}{2(1 - \gamma^2)\eta} N + \frac{2\hat{p}d_w\gamma}{1 - \gamma^2} N. \quad (2.108)$$

Thus,

$$\Delta NB'_2 = NB_r^{MM} - NB_r^{SM} = \frac{\eta N(d_w^2 + \hat{p}^2(1 - \frac{4\gamma^2}{1+\eta^2}))}{2(1 - \gamma^2)}. \quad (2.109)$$

Since

$$\begin{aligned} & d_w^2 + \hat{p}^2(1 - \frac{4\gamma^2}{1+\eta^2}) \\ &= \frac{1}{1+\eta^2}((d_w^2 + \hat{p}^2)(1 + \eta^2) - 4\hat{p}^2\gamma^2) \\ &= \frac{1}{1+\eta^2}(\hat{p}^2(1 + \eta^2 - 4\gamma^2) + d_w^2(1 + \eta^2)) \\ &> \frac{1}{1+\eta^2}(d_w^2\eta^2(1 + \eta^2 - 4\gamma^2) + d_w^2(1 + \eta^2)) \\ &= \frac{1}{1+\eta^2}d_w^2(1 + 2(1 - 2\gamma^2)\eta^2 + \eta^4) \\ &\geq \frac{1}{1+\eta^2}d_w^2(1 - \eta^2)^2 \\ &\geq 0, \end{aligned} \quad (2.110)$$

we have

$$\Delta NB'_2 = NB_r^{MM} - NB_r^{SM} > 0. \quad (2.111)$$

When  $p > \frac{d_w}{\eta}$ , the social net benefit in SM is,

$$NB_r^{SM} = \frac{\frac{1}{2}\hat{p}^2(\frac{1}{\eta} + \eta)}{1 - \gamma^2} N + \frac{2\hat{p}d_w\gamma}{1 - \gamma^2} N. \quad (2.112)$$

Thus,

$$\Delta NB'_3 = NB_r^{MM} - NB_r^{SM} = \frac{(d_w^2(1 + \eta^2) - \frac{4\eta^2\hat{p}^2\gamma^2}{1+\eta^2})N}{2\eta(1 - \gamma^2)}. \quad (2.113)$$

Note that in this situation, the realized social net benefit is still smaller than the

maximal social net benefit,

$$\Delta NB_3'' = NB_{Max} - NB_r^{SM} = \frac{d_w^2(1+\eta^2)N}{2\eta(1-\gamma^2)} > 0. \quad (2.114)$$

Therefore, in this situation, if  $\hat{p} > \frac{d_w(1+\eta^2)}{2\eta\gamma}$ , the SM leads to a higher net social benefit compared to MM; when  $\hat{p} \leq \frac{d_w(1+\eta^2)}{2\eta\gamma}$ , the MM leads to a higher net social benefit compared to SM. However, since  $\hat{p} > \frac{d_w(1+\eta^2)}{2\eta\gamma}$ , the water quality price is not binding and the landowners will produce according to carbon credit price, therefore, the SM and MM lead to identical outcome when the carbon benefit is ignored by the local regulator.

## Chapter 3

# Credit Stacking Policy and Landowners' Behavioral Responses

### 3.1 Introduction

Environmental credit markets have been developed to create incentives for ecosystem conservation. Well functioning ecosystems can provide several services simultaneously, such as water filtration, carbon sequestration, endangered species habitat and biodiversity enhancement. Regulatory-based markets require those who degrade such services to buy or create offsetting credits from elsewhere, such as required by the US Wetland Banking system under the Clean Water Act (Zedler, 2004). Environmental credit producers, including farmers and mitigation bankers, receive compensation by providing one or multiple environmental credits earned from their conservation activities. Recently, policy makers are debating whether credit producers shall be allowed to receive multiple payments for credits stacked from spatially overlapping areas, e.g.,

carbon credits and water quality improvement credits arising the same acre of land and a single production action. Ecological systems may create such considerations through a joint production process. In 2010, the Electric Power Research Institute (EPRI) conducted a national survey to solicit opinions on credit stacking issues. Different stakeholders, including credit sellers, researchers, and policy makers, showed a growing engagement and interest in environmental credit markets, with mixed reactions to the possibility of credit stacking.<sup>1</sup> Currently, policy makers often fail to provide a definite guideline on whether credit stacking should be allowed.<sup>2</sup>

In this paper, we compare these two policies by allowing producers to respond to different market institutions through influencing the natural production functions. With our theoretical analysis, we hope to assist policy design concerning credit stacking, the potential to sell jointly produced environmental credits arising from conservation or restoration of an ecosystem. According to our knowledge, Woodward (2011) stands as the first formal economic framework for the evaluation of stacking in a second best world for policy design. There is an emerging thread of research regarding the credit stacking issue, including both theoretical and empirical studies, often in a second-best context (Valcu et al., 2013; Gonzalez-Ramirez and Kling, 2015).

The credit stacking problem is sometimes framed as “double dipping” or “additionally”; these terms typically refer to a general problem: whether credit sellers shall be allowed to sell multiple credit types from the same land,<sup>3</sup> and definitions do

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<sup>1</sup>For detailed survey summary, see U.S National Opinion Survey on *Stacking Environmental Credits: Definition, Statues, and Predictions of Wetland, Species, Carbon and Water Quality Credit Stacking*, EPRI, 2011 behavioral Report, December 2011.

<sup>2</sup>On water quality trading programs, see 2003 Water Quality Trading Policy, Environmental Protection Agency; on carbon markets, see American Clean Energy and Security Act (CES), H.R. 2454 (2009). However, the Conservation Reserve Program (CRP) and the Environmental Quality Incentives Program (EQIP) allow the sale of environmental credits from enrolled lands. Cooley and Olander (2011) provide a detailed summary on stacking policies in various programs.

<sup>3</sup>Greenhalgh (2008) also used “bundled ecosystem markets”, terminology that can be regarded

differ in current literature. Here, credit stacking means “establishing more than one credit type on spatially overlapped areas”, a definition proposed by EPRI; double dipping concerns a situation where a credit producer sells credits in more than one market simultaneously, and when “credits are purchased, the necessary mitigation is not achieved because those same ecological values were used up under previous credit sales” (Fox, 2008).<sup>4</sup> Additionality occurs when an action creates an ecosystem enhancement beyond some baseline (Gillenwater, 2012; Banerjee et al., 2013). From a producer’s perspective, credit stacking is desirable because a managed ecosystem can create joint products that coexist in a given management site, while additionality criteria establish sellable credits only for units of ecosystem restored or service arising from explicit effort to generate output beyond a baseline linked to some other required compliance conditions. These two concepts focus on the origin and baseline of credits. Double dipping arises from imprecise standards when accounting for sale of a credit. For example, double dipping occurs when sellers get payment from different credit types in different markets (e.g., carbon and water quality markets), but these credits stemmed from the same action (e.g., wetland preservation, restoration, or creation) that was previously sold or entirely used for compliance with a regulation (e.g., under wetland mitigation or offset requirements). We view double dipping as receiving payment in full for a credit more than one time; that is, selling the same credit twice.

Another dimension of the credit stacking problem is the “bundle issue”. Bundling or unbundling concerns how the values of different types of natural resources are rep-

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as equivalent to selling multiple credits stacked on the same land.

<sup>4</sup>Double dipping can mean receiving payment from two or more sources in compensation for the same production decision. However, if aggregate marginal payments equal marginal costs such a practice may still be socially efficient. We note that while Woodward (2011) uses the term “double dipping”, his use of that term is consistent with our definition of credit stacking here.

resented, either together as one unit, or separated out in multiple units (Fox, 2008; Simonit and Perrings, 2013). Raudsepp-Hearne et al. (2010) present empirical identification of ecosystem bundles using spatial data in a mixed landscape. Liu and Swallow (2016) solicit individual preference regarding water quality credits linked to environmental co-benefits and illustrate a way of bundling different types of environmental benefits in transacting water quality credits. In economics, bundling occurs when a project receives a single payment for providing multiple ecosystem services. This issue is more related to specific purposes of mitigation policies. For example, a wetland conservation credit could include the water quality improvement and biodiversity or habitat services. Wetland banking may provide some additional benefits, such as carbon sequestration, which is often not perceived as included in the “wetland credit bundle”. If credit stacking is allowed, wetlands owners may receive additional return from credits for storing carbon. In Florida, the USFWS (U.S. Fish and Wildlife Service) does not allow credit stacking, while in California wetland owners can sell carbon credits from wetland banking under California’s Assembly Bill 32. Theoretically, the bundling issue is not a problem as long as all the bundled credits are clearly defined and the society can accurately account for each type of credit contained in the bundle. Thus, if credit stacking is allowed, a mitigation program would state explicitly which ecosystem assets or services are necessarily bundled and regarded as essential to program compliance, so that credit producers cannot get extra payment (no double dipping in the sense of double sale) from credits for which a producer has already been paid in full.

This paper considers the issue of whether producers shall be allowed to sell different credits stacked from the same project (e.g., same land parcel). Producers are not allowed to sell the same credit twice under any circumstance, so double dipping

is disallowed since we assume compensation paid for a credit constitutes payment in full and complete sale of that credit. We do not address the additionality problem explicitly since we cast the additionality as a definitional or an accounting issue: for example, in a wetland conservation contract, once the conservation target is clearly defined and strictly enforced, the extra water quality or carbon credits produced from additional management effort, if any, should be acknowledged; thus our contribution leaves whether rules of exchange should treat these extra credits differently than the baseline credits as an empirical question for future research. We assume distinct definitions of credits have been established.

Based on the above premises, we analyze how policy towards credit stacking might lead credit producers to choose different production technology in the long run and how such choices might affect the environmental outcome as well as the performance of credit markets. It is expected that credit sellers will alter their behaviors under alternative stacking policies; to our knowledge, this is the first study to address the reactions from credit sellers through the influence of technological choices in the long run. By behavioral reactions we refer to landowners' technological responses and change to existing plans, such as the type of crops or the change of a wetland mitigation restoration plan when the policy changes in the long run, subject to current production and engineering technology as well as natural constraints.

This paper builds on Woodward (2011), where credit stacking is framed as a multiple market institution (MM), and a policy preventing credit stacking is framed as a single market institution (SM). To set a tangible context, we will designate producers of environmental credits as "landowners", but readers should recognize the generality of the concept extends to any producers of such credits. We analyze a framework where landowners engage in ecosystem restoration and face choices to

push a managed or engineered ecosystem toward or away from one or more credit types. While the MM approach is optimal in a first-best world, Woodward shared a broad policy space under which the SM approach could be socially optimal in a second-best world. By incorporating the flexibility of the landowner or entrepreneur to influence a natural production technology for ecosystem services, the framework may substantially change the conditions over which proposed policies to prohibit stacking might be in the society's best interest in a second best world. While we draw several implications, our analyses follow from behavioral considerations that concern landowners' incentives and responses where credit stacking is not allowed.

Prohibiting stacking may cause private actions that lead to less well-rounded restoration of ecosystem functions. Also, a non-stacking policy may foreclose low cost production of ecosystem service benefits and desirable spinoffs from a more complete, well-functioning ecosystem. On the other hand, the flexibility to choose a different production technology may offset the inefficiency from the SM constraint in the long run as such flexibility may help landowners overcome some of the limitations brought by the SM. Therefore, it is uncertain whether the technological choice will offset or magnify the difference between SM and MM. These concerns are of timely importance as agencies face ongoing decisions to stimulate environmental markets.

## 3.2 Basic Model

In a general model, we consider a situation where there are  $N$  landowners that produce  $J$  types of credits in the market; each landowner  $i$  has a technology that enables a cost advantage in producing one type of credit, type  $j$ . The landowners may influence



the degree to which his or her land specializes in production of a credit type by choosing the specialization parameter,  $\eta_i$ , thereby altering the relative marginal cost of producing each different type of credit, which can be observed as altering the shape of the landowner's set of iso-cost curves. Let  $a_{ij}$  be the amount of type  $j$  pollutant that landowner  $i$  chooses to abate (or the amount of credit for pollution offsets of type  $j$  that the landowner choose to produce). Thus, the landowner  $i$ 's cost is determined by the production technology and the amount of credits produced. Specifically, we use  $g_i(\mathbf{a}_i)$  to denote the production cost and  $\mathbf{a}_i = \{a_{i1}, \dots, a_{ij}, \dots, a_{iJ}\}$  to denote a vector of credit types produced. Due to biophysical process of ecosystems (McCarney et al., 2008; Jackson et al., 2005), a certain level of complementarity exists in landowners' available production technologies. That is, given a fixed quantity of producing one credit, a cost minimizing landowner will inevitably produce some amount of another credit, which establishes a joint production problem.

The total social benefit is additively separable in each type of credit,<sup>5</sup> for simplicity, assuming  $B(\mathbf{A}) = \sum_j B_j(A_j)$ , where  $A_j$  is an index of the total credits (pollution abatements) that the landowners actually produce. In Woodward (2011), the production technology is constant, exogenously determined; we will then relax this assumption so that landowners can choose a different production technology to influence the production function. Therefore, the regulator wants to choose a cap vector  $\mathbf{A}$  or there is a market price vector  $\mathbf{p}$  such that the net social benefit is maximized:

$$\max \sum_{j=1}^J B_j(A_j) - \sum_{i=1}^N g_i(\mathbf{a}_i). \quad (3.1)$$

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<sup>5</sup>This is a simplifying assumption. Further research could explore the outcome when there is complementarity or substitutability in the benefit space between different types of credits.

The optimal cap  $\mathbf{A}^*$  or the market price  $\mathbf{p}^*$  can be found from the first order condition:

$$p_j^* = B'_j(\mathbf{A}^*) = \frac{\partial g_i(\mathbf{a}_i)}{\partial a_{ij}}, \forall i, j, \quad (3.2)$$

where  $a_{ij}$  identifies the amount of credit type  $j$  produced by landowner  $i$ . The regulator needs to have full information on both cost and benefit sides regarding the credit markets in order to set the optimal cap or regulate the market price. In reality, the regulator might not choose either target optimally, which can lead to distortion of credit production.

### 3.2.1 Allowing Credit Stacking, Multiple Market (MM)

Under the multiple market (MM) policy, the landowner can sell all types of tradable credits produced from the same land. We assume a landowner pursues the maximum profit by choosing the amount produced for each type. Given the price vector  $\mathbf{p}$ , the landowner maximizes profits:

$$\max_{a_{ij}} \sum_{j=1}^J p_j a_{ij} - g_i(\mathbf{a}_i). \quad (3.3)$$

The first order condition with respect to  $a_{ij}$  is:

$$p_j^* = \frac{\partial g_i(\mathbf{a}_i)}{\partial a_{ij}}. \quad (3.4)$$

Comparing equation (3.2) and (3.4), the solutions for the optimal choice of production amount  $a_{ij}$  are consistent with the solutions in the regulator's problem if the cap or

price is set optimally.<sup>6</sup>

### 3.2.2 Not Allowing Credit Stacking, Single Market (SM)

Under the SM policy, the landowner can only choose one type of credit to sell. Thus, the landowner will maximize profit by 1) choosing the type of credit and 2) the amount of credit to sell, without regard to quantities of credit types that the landowners will not sell. Given the market credit prices, the landowner maximizes profit:

$$\max_j \left\{ \max_{a_{ij}} (p_j a_{ij} - g_i(\mathbf{a}_i)) \right\}. \quad (3.5)$$

The decision to participate in market  $j$  will be optimal if

$$p_j a_{ij}^* - g_i(\mathbf{a}_i^{*[j]}) \geq p_k a_{ik}^* - g_i(\mathbf{a}_i^{*[k]}), \forall k \neq j \quad (3.6)$$

where  $\mathbf{a}_i^{*[j]}$  is the profit maximizing vector of abatement outcome conditional on the producer selling only in market  $j$ . Note that the total credits produced could be higher than the compliance requirement due to the complementarity in production if the cost minimization of producing one type of credit  $j$  would also produce some “by product” (or abatement) another type  $k$ . Under the SM policy towards stacking, this additional abatement would be omitted from the market addressing service type  $k$ . Advocates of the SM policy may view this outcome as a source of environmental improvement that is free. Our results below suggest that an advantage comes at the

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<sup>6</sup>Under these ideal circumstances, of course, the MM policy is optimal. The challenging policy concerns arise when the regulator incorrectly sets the target, due to inadequate knowledge of benefits. The second-best world may also arise with a missing regulatory market for one or more environmental services. Furthermore, the regulator may not fully anticipate landowners’ responses *ex ante*.

price of economic inefficiency and may even be a counter productive aspect of the SM policy.

### **3.3 Landowners Choose A Different Technology Parameter**

In this section, we analyze conditions that might lead the landowners to choose alternative technology parameters in the SM and MM policy. We focus on the choice of the specialization level, which concerns whether a landowner will choose a more balanced approach or a more specialized, possibly monoculture-based production approach.

#### **3.3.1 Difference in Choosing Credit Production Levels and Technology Parameters**

When the technology parameters are fixed, we only consider the influence of landowners' credit output on the total production cost, e.g., we assume the cost increases with the amount of carbon or water quality credits produced. However, the fixed technology parameters restrict landowners' flexibilities to behave in substantially different ways which, if allowed, could change the shape of the iso-cost curves under different stacking policies. Below we differentiate the influence of credit outputs and the influence of technological parameter choices on the production cost.

The choices of the credit outputs reflect the landowners' production decisions along the *same* iso-cost curve when the technology parameters are fixed. The landowners, such as farmers, may change the combination of carbon and water quality credits through the adaption of alternative management practices on the same parcel with

the same type of crop. Another example is that the wetland mitigation bankers may choose to produce a different combination of environmental credits on the same restoration site under the existing environmental engineering plan through the change of wetland best management practices.<sup>7</sup> Note that the choices on credit output do not involve a change of the location or the project site, the type of the agricultural crop or the change of a restoration plan.

However, the stacking policy may significantly affect farmers' potential revenue from selling environmental credits and they may respond to the policy change by choosing a different crop type or changing the location of cultivation (e.g., close or far away from a stream). A wetland mitigation banker may also choose a different restoration site or design a different restoration plan on the same site that substantially changes the wetland functions under different stacking policies. Wetland functions include nitrogen removal, phosphorous retention and habitat support. Wetland restorations could generally enhance the functionality compared to existing conditions, while the relative increase of a specific functionality depends on the restoration plan and often requires the wetland bankers to evaluate the tradeoffs between nutrient removal and habitat support (Adamus and Holzhauser, 2006; Erwin, 2009). The modification of a natural or created wetland to enhance one or more functions may negatively affect some other functions. Such activities effectively change the possible combination of credits produced and the shape of the iso-cost curves. For example, a wetland mitigation banker may choose a well-rounded wetland restoration plan when credit stacking is allowed, by reducing the potential maximum carbon credits from the restoration site and thus reduce the specialization level, in exchange for creating

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<sup>7</sup>Wetland best management practices are often targeted for specific environmental and ecosystem services, including the best management for forests, storm water management or debris removal. The change of wetland management practice alters the production of environmental credits.

more open water habitat for species that do not facilitate carbon storage.

Another example is that farmers may choose to alternate between different crops, such as corn or soybeans, since planting a crop on the same field in consecutive years reduces productivity. Crop rotation reduces fertilizer application and generates more water quality credits compared to the choice of not rotating (e.g., planting corn after corn). As a result, a farmer's rotation choice changes the specialization level in the water quality credit production and the rotation choice increases the production of potential maximum water quality credits (Arbuckle and Downing, 2001; Schilling and Libra, 2000). The rotation choice also influences carbon sequestration and soil carbon storage rates, thus changing the carbon supply (Antle et al., 2003). Therefore, depending on the market prices for environmental credits, the production technology employed can change under different stacking policies, while ignoring such changes could produce biased evaluation of alternative stacking policies.

### **3.3.2 A General Cost Function with Production Complementarity**

Below we present a general cost function that captures the complementarity nature in producing multiple types of credits. The market prices for carbon and water quality credits are  $p_c$  and  $p_w$ . We make the following assumptions regarding the cost function.

The specialization refers to a situation where the landowner has a cost advantage in producing one type of credit compared to the other. An increase in the specialization level implies such cost advantage further increases. For example, when a landowner has a cost advantage in producing carbon credits, we assume an increase in the specialization level will decrease the cost to produce carbon credit at the margin, and

increases the cost to produce water quality credit at the margin.

**Assumption 3.1.**  $g_{c\eta} < 0$ ,  $g_{w\eta} > 0$ .

**Assumption 3.2.**  $g_{ww} > 0$ ,  $g_{cc} > 0$  and  $g_{cw} < 0$ .

The  $g_{cc} > 0$  and  $g_{ww} > 0$  imply the increasing marginal cost assumption for both types of credits, while the increase of one credit will reduce the marginal cost of the other credit according to the negative cross partial derivative. As a result, the marginal cost of carbon credit increases with the amount of carbon credit and decreases with the amount of water quality credit. We adopt parallel assumptions for the marginal cost of the water quality credit. The cross partial derivative  $g_{cw} < 0$  captures the production complementarity.

**Proposition 3.1.** *When the market prices are  $p_c$  and  $p_w$ , and when  $g_{c\eta}/g_{w\eta} \leq g_{cc}/g_{cw}$ ,  $c_\eta \geq 0$  and  $w_\eta > 0$ ; when  $g_{cc}/g_{cw} < g_{c\eta}/g_{w\eta} < g_{cw}/g_{ww}$ ,  $c_\eta > 0$  and  $w_\eta < 0$ ; when  $g_{c\eta}/g_{w\eta} \geq g_{cw}/g_{ww}$ ,  $c_\eta < 0$  and  $w_\eta \leq 0$ .*

*Proof.* A landowner's profit is  $\pi(c, w) = p_c c + p_w w - g(\cdot)$  is maximized when the marginal cost equals the market price for both types of credits. We substitute in optimal supply functions to obtain

$$\begin{cases} p_c = \frac{\partial g}{\partial c}(c(\eta), w(\eta), \eta) \\ p_w = \frac{\partial g}{\partial w}(c(\eta), w(\eta), \eta), \end{cases} \quad (3.7)$$

which also hold true when  $p_c = 0$  or  $p_w = 0$ . Holding the credit prices constant and taking the total derivative w.r.t.  $\eta$ , we have

$$\begin{cases} g_{cc}c_\eta + g_{cw}w_\eta + g_{c\eta} = 0 \\ g_{cw}c_\eta + g_{ww}w_\eta + g_{w\eta} = 0. \end{cases} \quad (3.8)$$

Solving for  $c_\eta$  and  $w_\eta$ , we obtain

$$\begin{cases} c_\eta = \frac{g_{ww}g_{c\eta} - g_{w\eta}g_{cw}}{g_{cw}^2 - g_{cc}g_{ww}} \\ w_\eta = \frac{g_{cc}g_{w\eta} - g_{c\eta}g_{cw}}{g_{cw}^2 - g_{cc}g_{ww}}. \end{cases} \quad (3.9)$$

The profit is maximized when the determinant of the Hessian matrix for the profit function is positive (since  $g_{cc} > 0$  and  $g_{ww} > 0$  already hold), thus,

$$g_{cc}g_{ww} - g_{cw}^2 > 0. \quad (3.10)$$

Since  $g_{cw} < 0$ , the inequality (3.10) implies

$$g_{cc}/g_{cw} < g_{cw}/g_{ww}. \quad (3.11)$$

When

$$g_{cc}/g_{cw} < g_{c\eta}/g_{w\eta} < g_{cw}/g_{ww}, \quad (3.12)$$

according to equation (3.9), we have  $c_\eta > 0$  and  $w_\eta < 0$ . Similarly, when

$$g_{c\eta}/g_{w\eta} \geq g_{cw}/g_{ww}, \quad (3.13)$$

we have  $c_\eta < 0$  and  $w_\eta \leq 0$ . When

$$g_{c\eta}/g_{w\eta} \leq g_{cc}/g_{cw}, \quad (3.14)$$

we have  $c_\eta \geq 0$  and  $w_\eta > 0$ . □

Proposition 3.1 also indicates that when there is no complementarity in produc-



tion, i.e.,  $g_{cw} = 0$ ,

$$\begin{cases} c_\eta = \frac{g_{ww}g_{c\eta}}{g_{cw}^2 - g_{cc}g_{ww}} > 0 \\ w_\eta = \frac{g_{cc}g_{w\eta}}{g_{cw}^2 - g_{cc}g_{ww}} < 0, \end{cases} \quad (3.15)$$

the increase of specialization  $\eta$  will increase the carbon credit production and decrease the water quality credit production. Also, since  $g_{cw}$  represents the level of complementarity, we find that when the complementarity  $|g_{cw}| < |\frac{g_{cc}g_{w\eta}}{g_{c\eta}}|$ ,  $w_\eta < 0$  and when  $|g_{cw}| < |\frac{g_{ww}g_{c\eta}}{g_{w\eta}}|$ ,  $c_\eta > 0$ , suggesting that a moderate complementarity level has similar marginal effects as  $g_{cw} = 0$ ; however, a high complementarity may have a negative marginal effect on the carbon credit production and a positive effect on the water quality credit production.

Figure 3.1 presents the major insights from Proposition 3.1 graphically. In Figure 3.1, the horizontal axis is the quantity of carbon or water quality credit and the vertical axis is the market price. The marginal cost curves are increasing according to Assumption 3.2:  $g_{ww} > 0, g_{cc} > 0$ . We assume an initial condition (in the short run) where solid marginal cost curves lead to equilibrium quantities  $c_0$  and  $w_0$  at price  $p_c$  and  $p_w$  for carbon credit and water quality credit, respectively. The marginal cost curves for carbon and water quality credits are  $mc_{c0}$  and  $mc_{w0}$ . If there is no complementarity, i.e.,  $g_{cw} = 0$ , according to Assumption 3.1,  $g_{c\eta} < 0$ ,  $g_{w\eta} > 0$ , an increase in the specialization  $\eta$  will decrease the marginal cost of carbon credit and increase the marginal cost of water quality credit. As a result, the marginal cost curve will shift rightward for the carbon credit and leftward for the water quality credit, which would lead to the new marginal cost curves  $mc_{c1}$  and  $mc_{w1}$ . In this situation, the new equilibrium carbon credit  $c_1$  is higher than  $c_0$  and the new equilibrium water quality credit  $w_1$  is lower than  $w_0$ , which corresponds to the result  $c_\eta > 0$  and

$w_\eta < 0$ . However, based on Assumption 3.2,  $g_{cw} < 0$ , the change of carbon credit will also influence the marginal cost of water quality credit and *vice versa*. In our situation, an increase in production of the carbon credits will lower the marginal cost of production water quality credits, and thus, marginal cost curve  $mc_{w1}$  will shift rightward to  $mc_{w2}$ , offsetting the influence of a higher specialization level, the change of which will in turn affect the marginal cost of carbon credits, resulting in a shift from  $mc_{c1}$  to  $mc_{c2}$ . Therefore, when  $g_{cw} < 0$ , depending on the magnitude of the complementarity level, the final equilibrium credits  $c2$  and  $w2$  may be higher or lower than the original level  $c0$  and  $w0$ . The results  $c_\eta > 0$  and  $w_\eta < 0$  only hold when the magnitude of the complementarity level is small, as implied by Proposition 3.1.

**Example** A commonly used cost function follows the form (Helfand, 1991; Woodward, 2011):

$$g = \frac{1-\eta}{2}c^2 + \frac{1}{2(1-\eta)}w^2 - \gamma cw, \quad (3.16)$$

where  $c$  is the amount of carbon credits and  $w$  is the amount of water quality credits produced by a landowner. The parameter  $\eta$  reflects the cost effectiveness in producing carbon credit, which is the specialization level;  $\gamma = \frac{\partial^2 g}{\partial c \partial w}$  captures production complementarity level. If  $\gamma = 0$ , then there is no complementarity between the two types of credits, and credits stacking is not a problem since there is no by-product even if stacking is not allowed.<sup>8</sup> In the above cost function, the technology parameter  $\eta$  is restricted to  $\eta \in (0, 1)$ . The range of  $\eta$  may depend on the nature (ecosystem-

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<sup>8</sup>We assume that the landowner has no control over the complementarity level, which is determined by the natural production process. Furthermore, since increase  $\gamma$  will always lower the production cost, while the choice on the  $\eta$  determines the relative cost effectiveness, we focus on the landowner's flexibility of choosing a different specialization level.

dependent) constraints in practice, such as the geographical locations or the crop choice due to weather limitation. In case of mitigation banking, the range  $\eta$  may depend on the landscape restoration plans or the available environmental engineering technologies. This functional form satisfies our assumptions as  $g_{cc} = 1 - \eta > 0$ ,  $g_{ww} = \frac{1}{1-\eta} > 0$  and  $g_{cw} = -\gamma < 0$ . Also,  $g_{c\eta} = -c < 0$  and  $g_{w\eta} = \frac{w}{(1-\eta)^2} > 0$ . This specific functional form also satisfies the condition  $g_{cc}/g_{cw} < g_{c\eta}/g_{w\eta} < g_{cw}/g_{ww}$ .

Figure 3.2 shows the shape of iso-cost curves for a cost function that is consistent with our assumptions. The horizontal axis is the amount of carbon credit produced and the vertical axis is the amount of water quality credit produced. The cost level remains constant along the same curve. Point  $A$  is where the marginal cost of the carbon credit equals 0 and point  $B$  is where the marginal cost of water quality credit equals 0. The solid curve is the original iso-cost curve. This figure represents the case where the amount of carbon credits increases with the specialization level and the amount of water quality credits decrease with the specialization level.

In the single market institution, landowners are only allowed to sell credits in one market. We assume that an individual landowner has no influence on the market price. Without loss of generality, we consider the production in the carbon market and assume the landowners who have a cost advantage in producing carbon credits will only sell in the carbon market. Thus, the problem faced by the landowner specialized in carbon production is:

$$\max_{c,w} p_c c - g(c, w, \eta), \quad (3.17)$$

where  $p_c$  is the market price for the carbon credit,  $g(\cdot)$  is the cost function. The  $\eta$  is the specialization level and is considered fixed in the short run. The market price for carbon  $p_c$  is fixed, as the landowners are price takers. Since the landowner's

production choice for  $c$  is a function of the specialization level, in the short run when the landowner is unable to change the specialization level, the landowner chooses  $(c_s, w_s)$  to maximize profit for any specialization level  $\eta$ . The subscript  $s$  indicates the production in the SM. In this situation, the optimal supply functions are:

$$\begin{cases} c_s = c(\eta, p_c) \\ w_s = w(\eta, p_c) \end{cases} \quad (3.18)$$

In the long run, the problem faced by the landowner specialized in carbon production is:

$$\max_{c, w, \eta} p_c c - g(c, w, \eta), \quad (3.19)$$

since the landowner is now able to change the specialization level  $\eta$ , the landowner chooses  $(c_s^l, w_s^l, \eta_s^l)$  to maximize profit. In this situation, the supply functions are:

$$\begin{cases} c_s^l = c(p_c) \\ w_s^l = w(p_c) \\ \eta_s^l = \eta(p_c) \end{cases} \quad (3.20)$$

In the multiple market (MM) institution, landowners can sell credits in both markets. As before, we assume that an individual landowner has no influence on the market price for either type of credit. We now consider the equilibrium production in the carbon market and the water quality market. The problem faced by the landowner is:

$$\max_{c, w} p_c c + p_w w - g(c, w, \eta), \quad (3.21)$$

where  $p_w$  is the market price for water quality credits since now landowners can sell

in both markets. As before, we assume that in the short run, the specialization parameter  $\eta$  is fixed and we solve for the optimal supply functions. In this situation, the optimal supply functions are:

$$\begin{cases} c_m = c(\eta, p_c, p_w) \\ w_m = w(\eta, p_c, p_w). \end{cases} \quad (3.22)$$

In the long run, the problem faced by the landowner specialized in carbon production in the MM is:

$$\max_{c, w, \eta} p_c c + p_w w - g(c, w, \eta), \quad (3.23)$$

since the landowner is now able to change the specialization level  $\eta$ , the landowner chooses  $(c_m^l, w_m^l, \eta_m^l)$  to maximize profit. In this situation, the first order conditions are:

$$\begin{cases} p_c - \frac{\partial g}{\partial c} = 0 \\ p_w - \frac{\partial g}{\partial w} = 0 \\ -\frac{\partial g}{\partial \eta} = 0 \end{cases} \quad (3.24)$$

and the supply functions are

$$\begin{cases} c_m^l = c(p_c, p_w) \\ w_m^l = w(p_c, p_w) \\ \eta_m^l = \eta(p_c, p_w). \end{cases} \quad (3.25)$$

**Proposition 3.2.** *In the MM, the optimal specialization level in the long run is lower than the optimal specialization level in the SM ( $\eta_m^l < \eta_s^l$ ) when  $w_\eta < 0$ , and  $\eta_m^l > \eta_s^l$  if  $w_\eta > 0$ .*

*Proof.* From the landowner's perspective, the SM is equivalent to a situation where

the  $p_w = 0$ . Given equation (3.24), profit maximum implies:

$$\frac{\partial \eta_m^l}{\partial p_w} = \frac{\begin{vmatrix} -g_{cc} & -g_{cw} & 0 \\ -g_{cw} & -g_{ww} & -1 \\ -g_{c\eta} & -g_{w\eta} & 0 \end{vmatrix}}{\begin{vmatrix} -g_{cc} & -g_{cw} & -g_{c\eta} \\ -g_{cw} & -g_{ww} & -g_{w\eta} \\ -g_{c\eta} & -g_{w\eta} & -g_{\eta\eta} \end{vmatrix}} = \frac{g_{cc}g_{w\eta} - g_{cw}g_{c\eta}}{(-)}. \quad (3.26)$$

According to Proposition 3.1, we can sign the partial derivative  $\frac{\partial \eta_m^l}{\partial p_w}$ .  $\square$

Similarly, when  $g_{cw}$  represents the level of complementarity, we find that when the complementarity  $|g_{cw}| < |\frac{g_{cc}g_{w\eta}}{g_{c\eta}}|$ ,  $w_\eta < 0$  and  $\eta_m^l(p_w) < \eta_m^l(0) = \eta_s^l$ , the MM leads to a less specialized production technology with a moderate complementarity level; however, the MM may lead to a highly specialized production technology at a high complementarity level. Also, we can infer that when  $g_{cw} = 0$  and there is no complementarity in production,  $\eta_m^l < \eta_s^l$ .

### 3.4 Social Welfare Implications

In this section, we calculate the value of produced environmental credits and focus on the influence of specialization choice on the overall net social benefits under the two market policies (SM and MM). Assume there are  $N$  heterogenous landowners and each landowner has an initial specialization level  $\eta_{0i}$ . In the short run, the production bundle  $(c'_i, w'_i)$  maximizes the following social net benefit function given the fixed

specialization parameters  $\eta_{i0}$

$$NB_{sr} = B_c(\sum_i c_i) + B_w(\sum_i w_i) - \sum_{i=1}^N g(c_i, w_i, \eta_{0i}) \quad (3.27)$$

where the  $B_c(\cdot)$  and  $B_w(\cdot)$  are the benefit functions for carbon and water quality credits, respectively, with  $B'(\cdot) > 0$  and  $B''(\cdot) \leq 0$ . The subscript  $i$  indexes the landowners AND thus  $g(c_i, w_i, \eta_{0i})$  is the cost function for landowner  $i$ . For simplicity, we assume a constant marginal carbon sequestration benefit  $d_c$  at the market price  $p_c$  and a constant water quality improvement benefit  $d_w = p_w$ . Therefore, the first order conditions imply  $d_c = p_c = \frac{\partial g_i}{\partial c_i}$  and  $d_w = p_w = \frac{\partial g_i}{\partial w_i}$ .

In the MM, the landowner chooses credit production such that  $d_c = p_c = \frac{\partial g_i}{\partial c_i}$  and  $d_w = p_w = \frac{\partial g_i}{\partial w_i}$  by maximizing profit according to equation (3.21), while in the SM,  $d_w = p_w \neq \frac{\partial g_i}{\partial w_i} = 0$  for any positive water quality credit price  $p_w$  when landowner  $i$  chooses to participate in the carbon market. Therefore, the MM institution maximizes the net social benefit in the short run (given a fixed specialization parameter). The net social benefit difference between SM and MM in the short run is

$$\begin{aligned} \Delta NB_{sr} &= NB_{sr}^m - NB_{sr}^s = d_c \sum_i (c_m(\eta_{0i}) - c_s(\eta_{0i})) + d_w \sum_i (w_m(\eta_{0i}) - w_s(\eta_{0i})) \\ &+ \sum_i g(c_s(\eta_{0i}), w_s(\eta_{0i}), \eta_{0i}) - \sum_i g(c_m(\eta_{0i}), w_m(\eta_{0i}), \eta_{0i}), \end{aligned} \quad (3.28)$$

where the subscripts  $s$  and  $m$  differentiate the single market ( $s$ ) and the multiple market ( $m$ ) institution. In the long run, when the landowner can choose the specialization parameter, the credit production and the specialization level  $(c_i^*, w_i^*, \eta_i^*)$  maximize the following social net benefit function

$$NB_{lr} = B_c(\sum_i c_i) + B_w(\sum_i w_i) - \sum_i g(c_i, w_i, \eta_i). \quad (3.29)$$

The first order conditions imply  $d_c = p_c = \frac{\partial g_i}{\partial c_i}$  and  $d_w = p_w = \frac{\partial g_i}{\partial w_i}$  and  $\frac{\partial g(\cdot)}{\partial \eta_i} = 0$  for any landowner  $i$ . Also, note that all the first order conditions are satisfied in the MM thus MM also maximizes the net social benefit in the long run. However, since  $d_w = p_w \neq \frac{\partial g_i}{\partial w_i}$  in SM, the realized net social benefit in MM is weakly higher than SM. Thus we have Proposition .

**Proposition 3.3.** *MM leads to a weakly higher net social benefit than SM both in the short run where the landowners face a fixed specialization level, and in the long run, when the landowners could change the specialization level.*

Proposition 3.3 shows that MM is efficient in both the short run and long run. The SM serves as an extra constraint and creates efficiency loss compared to MM. Thus, in the first-best world, the MM always performs as well or better than the SM even when the landowner can choose a different specialization level.

Another interesting question is whether the choice of the specialization parameter offsets or magnifies the inefficiency in SM in the long run. Let  $\eta_{im}^*$  and  $\eta_{is}^*$  denote the landowner  $i$ 's optimal specialization choice in the MM and SM respectively. Then, the social net benefit difference between SM and MM in the long run is

$$\begin{aligned} \Delta NB_{lr} &= NB_{lr}^m - NB_{lr}^s = d_c \sum_i (c_m(\eta_{im}^*) - c_s(\eta_{is}^*)) + d_w \sum_i (w_m(\eta_{im}^*) - w_s(\eta_{is}^*)) \\ &+ \sum_i g(c_s(\eta_{is}^*), w_s(\eta_{is}^*), \eta_{is}^*) - \sum_i g(c_m(\eta_{im}^*), w_m(\eta_{im}^*), \eta_{im}^*) \end{aligned} \quad (3.30)$$

If  $\Delta NB_{sr} > \Delta NB_{lr}$ , the inefficiency in the SM is partially offset by the flexibility to choose a specialization parameter in the long run, suggesting the value of such flexibility is higher in a world with a pre-existing distortion (e.g., under the SM institution) compared to the MM. On the other hand, if  $\Delta NB_{sr} < \Delta NB_{lr}$ , the inefficiency in the SM is further magnified by the flexibility to choose a specialization



parameter in the long run. To compare the difference between the net social benefit in the short run and in the long run, we maintain the assumption that  $d_w = p_w$  and  $d_c = p_c$ . In the SM, the landowners are treating  $p_w = 0$  compared to the MM where  $p_w = d_w$ . Denote the water quality credits produced in the long run and short run at a price  $\tilde{p}_w$  as  $w^l(\tilde{p}_w)$  and  $w^s(\tilde{p}_w)$ , respectively. Note that  $\tilde{p}_w$  is now a variable representing the water quality credit price and does not necessarily equal the marginal benefit  $d_w$ .

**Proposition 3.4.** *If  $w^l(\tilde{p}_w) > w^s(\tilde{p}_w)$ , a landowner's profit difference in the SM and MM institution increases due to the flexibility to choose a specialization parameter in the long run. If  $w^l(\tilde{p}_w) < w^s(\tilde{p}_w)$ , a landowner's profit difference in the SM and MM decreases due to the flexibility to choose a specialization parameter in the long run.*

*Proof.* For any landowner  $i$ , we assume the initial specialization parameter is  $\eta_0$ , and define the difference between long run and short run profit  $\Delta\pi$  as a function of water quality credit price  $\tilde{p}_w$ ,

$$\begin{aligned} \Delta\pi(\tilde{p}_w) &= \pi^l(c(p_c, \tilde{p}_w, \eta(p_c, \tilde{p}_w)), w(p_c, \tilde{p}_w, \eta(p_c, \tilde{p}_w)), p_c, \tilde{p}_w, \eta(p_c, \tilde{p}_w), \eta_0) \\ &- \pi^s(c(p_c, \tilde{p}_w, \eta_0), w(p_c, \tilde{p}_w, \eta_0), p_c, \tilde{p}_w, \eta_0), \end{aligned} \quad (3.31)$$

where the landowner's long term profit function is  $\pi^l(p_c, \tilde{p}_w, \eta_k, \eta_0)$  and short term profit function is  $\pi^s(p_c, \tilde{p}_w, \eta_0)$ . The superscript  $l$  or  $s$  indicates if the profit function is evaluated in the short run or long run. The  $\eta(p_c, \tilde{p}_w)$  is the specialization level chosen in the long run, which depends on the market prices. In the short run, the specialization level  $\eta$  is fixed at  $\eta_0$ , while in the long run the specialization level  $\eta$  is optimized given the market price  $p_c$  and  $\tilde{p}_w$ . Take the total derivative of  $\Delta\pi$  with

respect to  $\tilde{p}_w$ ,

$$\begin{aligned} \frac{d\Delta\pi}{d\tilde{p}_w} &= \frac{\partial\pi^l}{\partial c} \left( \frac{\partial c}{\partial \tilde{p}_w} + \frac{\partial c}{\partial \eta_k} \frac{\partial \eta_k}{\partial \tilde{p}_w} \right) + \frac{\partial\pi^l}{\partial w} \left( \frac{\partial w}{\partial \tilde{p}_w} + \frac{\partial w}{\partial \eta_k} \frac{\partial \eta_k}{\partial \tilde{p}_w} \right) + \frac{\partial\pi^l}{\partial \eta_k} \frac{\partial \eta_k}{\partial \tilde{p}_w} + \frac{\partial\pi^l}{\partial \tilde{p}_w} \\ &- \left( \frac{\partial\pi^s}{\partial c} \frac{\partial c}{\partial \tilde{p}_w} + \frac{\partial\pi^s}{\partial w} \frac{\partial w}{\partial \tilde{p}_w} + \frac{\partial\pi^s}{\partial \tilde{p}_w} \right). \end{aligned} \quad (3.32)$$

According to the envelop theorem,

$$\frac{\partial\pi^l}{\partial c} = \frac{\partial\pi^l}{\partial w} = \frac{\partial\pi^l}{\partial \eta_k} = \frac{\partial\pi^s}{\partial c} = \frac{\partial\pi^s}{\partial w} = 0. \quad (3.33)$$

As a result, equation (3.32) becomes,

$$\frac{d\Delta\pi}{d\tilde{p}_w} = \frac{\partial\Delta\pi}{\partial \tilde{p}_w} = \frac{\partial\pi^l}{\partial \tilde{p}_w} - \frac{\partial\pi^s}{\partial \tilde{p}_w} = w^l(\tilde{p}_w) - w^s(\tilde{p}_w). \quad (3.34)$$

When  $w^l(\tilde{p}_w) > w^s(\tilde{p}_w)$ ,  $\forall \tilde{p}_w$ , a landowner's profit difference between the short run and long run increases as the  $\tilde{p}_w$  increases, therefore  $\frac{\partial\Delta\pi}{\partial \tilde{p}_w} > 0$ . When  $w^l(\tilde{p}_w) < w^s(\tilde{p}_w)$ ,  $\forall \tilde{p}_w$ , a landowner's profit difference between the short run and long run increases as the  $\tilde{p}_w$  decreases, therefore  $\frac{\partial\Delta\pi}{\partial \tilde{p}_w} < 0$ .

As a result, we find that  $\Delta\pi(\tilde{p}_w = d_w) > \Delta\pi(\tilde{p}_w = 0)$ , which implies  $\pi^l(\tilde{p}_w = d_w) - \pi^s(\tilde{p}_w = d_w) > \pi^l(\tilde{p}_w = 0) - \pi^s(\tilde{p}_w = 0)$ , or  $\pi^l(\tilde{p}_w = d_w) - \pi^l(\tilde{p}_w = 0) > \pi^s(\tilde{p}_w = d_w) - \pi^s(\tilde{p}_w = 0)$ , suggesting the difference between profit in MM and profit in SM is greater in the long run than in the short run.

□

When the market price equals the marginal social benefit for the two types of credits, the difference in social net benefits between the long run and short run is

given by

$$\begin{aligned}\Delta NB_{lr} - \Delta NB_{sr} &= NB_{lr}(d_w) - NB_{sr}(d_w) - (NB_{lr}(0) - NB_{sr}(0)) \\ &= \sum_i (\Delta \pi_i(d_w) - \Delta \pi_i(0) - d_w(w_i^l(0) - w_i^s(0))),\end{aligned}\tag{3.35}$$

where the net social benefit is expressed as a function of the water quality credit price  $\tilde{p}$ .

**Proposition 3.5.** *If  $w^l(\tilde{p}_w) + w^l(0) > w^s(\tilde{p}_w) + w^s(0)$ , the inefficiency in SM is magnified when producers have the flexibility to choose a specialization parameter in the long run. If  $w^l(\tilde{p}_w) + w^l(0) < w^s(\tilde{p}_w) + w^s(0)$ , the inefficiency in SM is partially offset by the flexibility to choose a specialization parameter in the long run.*

*Proof.* For any landowner  $i$ , we assume the initial specialization parameter is  $\eta_0$  and define

$$\begin{aligned}\Delta NB^0(\tilde{p}_w) &= \pi^l(c(p_c, \tilde{p}_w, \eta_k(p_c, \tilde{p}_w)), w(p_c, \tilde{p}_w, \eta_k(p_c, \tilde{p}_w)), p_c, \tilde{p}_w, \eta_k(p_c, \tilde{p}_w), \eta_0) \\ &\quad - \pi^s(c(p_c, \tilde{p}_w, \eta_0), w(p_c, \tilde{p}_w, \eta_0), p_c, \tilde{p}_w, \eta_0) \\ &\quad - (d_w - \tilde{p}_w)(w^l(p_c, 0, \eta_k(p_c, 0), \eta_0) - w^s(p_c, 0, \eta_0)),\end{aligned}\tag{3.36}$$

where the landowner's long term profit function is  $\pi^l(p_c, \tilde{p}_w, \eta_k, \eta_0)$  and short term profit function is  $\pi^s(p_c, \tilde{p}_w, \eta_0)$ . In the MM, when  $\tilde{p}_w = d_w$ , then

$$\Delta NB^0(d_w) = \pi^l(p_c, d_w, \eta_k, \eta_0) - \pi^s(p_c, d_w, \eta_0).\tag{3.37}$$

In contrast,  $\tilde{p}_w = 0$  in the SM, so

$$\Delta NB^0(0) = \pi^l(p_c, 0, \eta_k, \eta_0) - \pi^s(p_c, 0, \eta_0) - d_w(w^l(p_c, 0, \eta_k(p_c, 0), \eta_0) - w^s(p_c, 0, \eta_0)).\tag{3.38}$$

Note that the function  $NB^0(\tilde{p}_w)$  only gives the net social benefit difference between short run and long run at  $\tilde{p}_w = d_w$  in equation (3.37) and  $\tilde{p}_w = 0$  in equation (3.38) and does not reflect the net social benefit difference for all  $\tilde{p}_w \in (0, d_w)$ . However, since we only care about the comparison at  $\tilde{p}_w = d_w$  and  $\tilde{p}_w = 0$ , we can use the property of the function  $\Delta NB^0(\tilde{p}_w)$  to compare  $\Delta NB(d_w)$  and  $\Delta NB(0)$ . In the short run, the specialization level  $\eta$  is fixed at  $\eta_0$  while in the long run the specialization level  $\eta$  is optimized given the market price  $p_c$  and  $\tilde{p}_w$ . Take the total derivative of  $\Delta NB^0$  with respect to  $\tilde{p}_w$ ,

$$\begin{aligned} \frac{d\Delta NB^0}{d\tilde{p}_w} &= \frac{\partial \pi^l}{\partial c} \left( \frac{\partial c}{\partial \tilde{p}_w} + \frac{\partial c}{\partial \eta_k} \frac{\partial \eta_k}{\partial \tilde{p}_w} \right) + \frac{\partial \pi^l}{\partial w} \left( \frac{\partial w}{\partial \tilde{p}_w} + \frac{\partial w}{\partial \eta_k} \frac{\partial \eta_k}{\partial \tilde{p}_w} \right) + \frac{\partial \pi^l}{\partial \eta_k} \frac{\partial \eta_k}{\partial \tilde{p}_w} + \frac{\partial \pi^l}{\partial \tilde{p}_w} \\ &- \left( \frac{\partial \pi^s}{\partial c} \frac{\partial c}{\partial \tilde{p}_w} + \frac{\partial \pi^s}{\partial w} \frac{\partial w}{\partial \tilde{p}_w} + \frac{\partial \pi^s}{\partial \tilde{p}_w} \right) + w^l(0) - w^s(0), \end{aligned} \quad (3.39)$$

where the superscript  $l$  or  $s$  indicates if the profit function is evaluated in the short run or in the long run. According to the envelop theorem,

$$\frac{\partial \pi^l}{\partial c} = \frac{\partial \pi^l}{\partial w} = \frac{\partial \pi^l}{\partial \eta_k} = \frac{\partial \pi^s}{\partial c} = \frac{\partial \pi^s}{\partial w} = 0. \quad (3.40)$$

As a result, equation (3.39) becomes,

$$\frac{\partial \Delta NB^0}{\partial \tilde{p}_w} = \frac{\partial \pi^l}{\partial \tilde{p}_w} - \frac{\partial \pi^s}{\partial \tilde{p}_w} + w^l(0) - w^s(0) = w^l(\tilde{p}_w) - w^s(\tilde{p}_w) + w^l(0) - w^s(0). \quad (3.41)$$

When  $w^l(\tilde{p}_w) + w^l(0) > w^s(\tilde{p}_w) + w^s(0)$ ,  $\forall \tilde{p}_w$ , the inefficiency in SM is magnified by the flexibility to choose a specialization parameter in the long run. When  $w^l(\tilde{p}_w) + w^l(0) < w^s(\tilde{p}_w) + w^s(0)$ ,  $\forall \tilde{p}_w$ , the inefficiency in SM is offset by the flexibility to choose a specialization parameter in the long run.  $\square$

Below we use  $\eta_s^s$  and  $\eta_s^l$  to denote the specialization choice in the SM in the short

run and long run, respectively, and use  $\eta_m^s$  and  $\eta_m^l$  to denote the specialization choice in the MM in the short run and long run. If the stacking policy changes from SM to MM when the specialization level is already optimized in the SM (e.g.,  $\eta_s^s = \eta_s^l = \eta_m^s$ ), according to Proposition 3.2, the optimal specialization level in the MM will be lower ( $\eta_m^l < \eta_m^s$ ) if  $w_\eta < 0$  and will be higher ( $\eta_m^l > \eta_m^s$ ) if  $w_\eta > 0$  in the long run. Thus, landowners' profits and the net social benefits depend on the relative magnitude of  $w^l(\tilde{p}_w)$  and  $w^s(\tilde{p}_w)$ ,  $\forall \tilde{p}_w$ .<sup>9</sup> When  $w_\eta < 0$ , since  $\eta_m^l < \eta_m^s$ ,  $w^l = w(\eta_m^l) > w(\eta_m^s) = w^s$ , the inefficiency in SM is magnified by the flexibility to choose a specialization parameter in the long run. When  $w_\eta > 0$ , since  $\eta_m^l > \eta_m^s$ ,  $w^l = w(\eta_m^l) > w(\eta_m^s) = w^s$  still holds, we conclude that in this situation, the inefficiency in SM is also magnified by the flexibility to choose a specialization parameter in the long run as well.

Based on the commonly used cost function specified in equation (3.16), we assume the profit function is

$$\pi = p_c c + p_w w - \left( \frac{1-\eta}{2} c^2 + \frac{1}{2(1-\eta)} w^2 - \gamma * cw \right). \quad (3.42)$$

For any level  $\eta$ , the supply functions are:

$$c = \frac{\frac{p_c}{1-\eta} + p_w \gamma}{1 - \gamma^2}, w = \frac{(1-\eta)p_w + \gamma \hat{p}}{1 - \gamma^2}, \quad (3.43)$$

which implies  $c_\eta = \frac{p_c}{(1-\gamma^2)(1-\eta)^2} > 0$  and  $w_\eta = \frac{-p_w}{1-\gamma^2} < 0$ . According to equation (3.41),

$$w^l(p_w) + w^l(0) - w^s(p_w) - w^s(0) = -\frac{(\eta_m^l - \eta_m^s)p_w}{1 - \gamma^2} - \frac{(\eta_s^l - \eta_s^s) * 0}{1 - \gamma^2}. \quad (3.44)$$

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<sup>9</sup>When  $\eta_s^s = \eta_s^l$ , the specialization level in SM is already optimized,  $w^l(0) = w^s(0)$ .

Therefore, if the stacking policy changes from SM to MM when the specialization level is already optimized in the SM (e.g.,  $\eta_s^s = \eta_s^l = \eta_m^s$ ), in the long run, since  $w_\eta < 0$ ,  $\eta_m^l < \eta_s^l$ , the landowner's profit will further increase and the net social benefits will further increase as well.

### 3.5 Conclusions and Discussion

In this paper, we provide an analytical framework to study landowners' responses toward a policy implementing or prohibiting credit stacking, focusing on a landowner's specialization choice in the long run. We are able to compare the landowners' optimal specialization choices in different market institutions. Consistent with our intuition, we find that when allowing credit stacking, landowners tend to choose a more balanced production technology; when credit stacking is not allowed, landowners tend to choose a more specialized production technology. The multiple market institution leads to a more balanced production approach from the market participants. However, our results also point out when there is a high complementary production technology, this result will change and the MM institution may lead to a more specialized production in the long run.

This study focuses on the behavioral responses to the credit stacking policy by allowing landowners to choose a different specialization parameter in the long run. It is an advancement compared to stylized analysis where such behavioral or long-term responses are entirely ignored in the presence of a fundamental policy change. Recently, an increasing number of empirical studies have started to focus on the “unexpected” outcomes, or unintended consequences brought about by certain policies (Gneezy et

al, 2011). One of the main reasons a policy often brings limited or even counter-vailing consequences is that policy makers often ignore agents' choice and flexibility which would often offset the incentive which a policy intends to introduce to discourage less desirable outcome. Our results imply that the SM restriction will magnify the inefficiency compared to the MM in the long run, regardless the level of complementarity. We expect the choice of the specialization level will reduce production of the types of credits which have no tradable markets, moving these environmental quality dimensions further away from the optimal production, in addition to a below-optimal production level generated in the first place, subject to the constraint on the complementarity level in the paper.

It is also important to consider additional benefit from a more balanced production approach, such as the biodiversity enhancement value. Biodiversity is an important criteria in assessing ecological benefits. A balanced production function presumably leads to a more stable ecosystem, which may offer rich biodiversity values which cannot be realized from monoculture-based practices. Nelson et al. (2009) find that a higher level of ecosystem service variety also implies a higher level of biodiversity through spatial modeling. As a result, the payment for ecosystem services of various types may simulate a higher level of biodiversity as the ecosystem service and biodiversity conservation are highly aligned (Polasky et al., 2012). Thus, ideally, we want to incorporate the enhanced biodiversity value into the benefit function. However, it is hard to compare the relative value of biodiversity with the value of other environmental credits. Note that if biodiversity can be traded as a credit as well (Bull et al., 2013), the landowner may acquire extra revenue from a balanced production.

We use carbon and water quality credit as an example to illustrate the credit stacking problem throughout the paper. The carbon emission has global impact,

thus, to address the externality problem, we may need coordination among different nations to form a uniform global carbon price. Since a global carbon market can be very competitive, an individual landowner may have little influence (Weitzman, 2014). On the other hand, water quality credits often have limited impact, usually within a watershed. Thus, the technology choice by a single landowner may have a larger influence on the local water quality market. Our framework does not consider the heterogeneity in the types of credits and how the choice of the specialization level would interact with heterogeneous credit types. We also maintain the assumption that the water quality credit price is the same in the short run and in the long run. These limitations provide opportunities for future research.

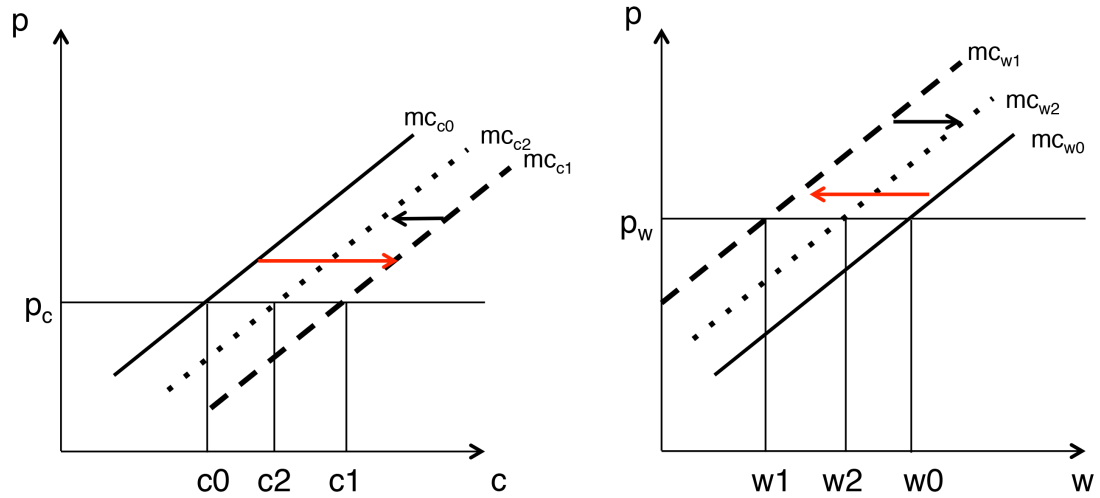
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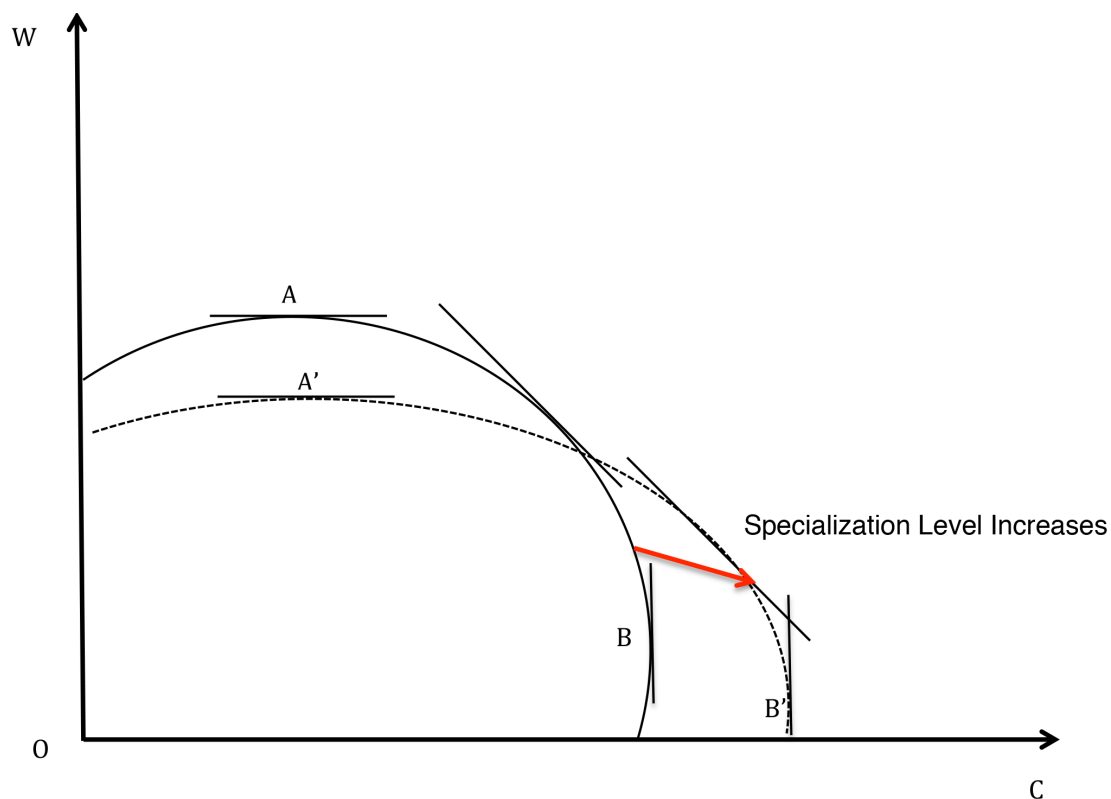
are our own.

FIGURE 3.1: The Influence of Production Complementarity.



Note: This figure shows the influence of production complementarity on the marginal cost curves. The horizontal axis is the quantity of carbon or water quality credit and the vertical axis is the market price. The marginal cost curves are increasing for both types of credits. Without production complementarity, the marginal cost curves  $mc_{c0}$  and  $mc_{w0}$  shift to  $mc_{c1}$  and  $mc_{w1}$  as the specialization level increases, respectively for carbon and water quality credit. Production complementarity may further shift the marginal cost curves  $mc_{c1}$  and  $mc_{w1}$  to  $mc_{c2}$  and  $mc_{w2}$  in the equilibrium.

FIGURE 3.2: The Cost Curve and the Change of the Specialization Level.



Note: This figure illustrates a general cost function that satisfies our assumptions. The horizontal axis and vertical axis are the amount of carbon credit and water quality credit produced, respectively. Point  $A$  is where the marginal cost of carbon equals 0 and point  $B$  is where the marginal cost of water quality credit equals 0. There are two iso-cost curves that differ in the specialization level and show the change from the short run to the long run. This figure shows the situation where the equilibrium water quality credit will decrease with the increase of the specialization level and the equilibrium carbon credit will increase with the increase of specialization level.

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