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Multi-Credit Market, Landowners' Responses, and Cost-Effectiveness of Credit Stacking Policy

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Abstract:

Credit stacking involves the sale of multiple types of environmental credits from a single, spatially defined project. The practice is controversial because environmental advocates suspect (a) producers may undermine the principle of additionality by extracting unearned profits through the sale of by-products from actions taken based on the incentives for a single credit-type, (b) society may lose the opportunity for free environmental improvements when complementary or joint production creates such by-products, or (c) broader environmental quality may decline by allowing polluters' cheaper or easier compliance with off-set requirements, weakening incentives to avoid initiating degradation. Previous research ignores producers' potential responses when the credit stacking policy changes. This paper offers a framework to analyze the interaction between credit stacking policy and producers' choices—especially regarding their choice of production technology—and the implications for the relative advantages of alternative stacking policies for environmental markets.

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1. Introduction

In the last fifteen to twenty years, and particularly in the U.S. since the 2008 Farm Bill created the USDA Office of Environmental Markets, environmental policy development has increasingly focused on market-based approaches to the provision of ecosystem services, the benefits that nature provides to human well-being (Ferraro, 2008; Jack et al., 2008; MEA, 2005; Gómez-Baggethun et al., 2010). As a result, 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 landowners (or farmers) and mitigation bankers, may receive compensation through environmental markets by providing one or multiple environmental credits earned from their conservation activities or from implementing new best management practices.

Recently, policymakers are debating whether credit producers shall be allowed to receive payments for multiple types of credits stacked from spatially overlapping areas, e.g., carbon credits and water quality improvement credits arising from the same acre of land and a single production action (Morgan et al., 2014). An example may be planting a vegetated buffer strip that produces two effects: it captures excess nutrients that would otherwise enter rivers through run-off from agricultural fields, by using dense grasses that stores carbon below ground in a thick root mass. The former effect could earn water quality credits, while the latter effect earns carbon credits. Ecological systems may unavoidably create such multiple outputs through a joint production process (McCarney et al., 2008).

In this context, a particular policy attempts to constrain or prevent what the literature has called credit stacking, sometimes using the term double dipping synonymously (Cooley and Olander 2012; Fox 2008; Fox et al. 2011; Valcu et al., 2013; González-Ramírez and Kling, 2015). We attempt to distinguish these terms based on possible differences in focus held by various commentators, with the intent only to establish a brief basis for clarifying our contribution rather than investing space in a long semantic debate. We view credit stacking as consistent with the concept of joint production and sales in economics, where a producer creating more than one product from a single process is able to sell the final products separately. In a joint production framework, that producer selects his or her inputs based on understanding the revenue potential of the full suite of saleable products. However, some commentators may identify situations where they believe a producer, such as a farmland owner, is being paid twice for the same action. These commentators might apply the label double dipping, possibly to convey an aversion to the idea of dual sales of the same product, which would undermine the principle of additionality in measuring and compensating for the provision of ecosystem services (Batie, 2003). But functional complexities of ecosystems establish joint production as reality while obfuscating a universally intuitive delineation of legitimate credit stacking, which would be consistent with Pareto efficiency in production, as distinct from windfall profiteering from the dual sale of a single contract.

For example, if regulators establish that impacts on (degradations of) wetlands require an off-setting wetland credit, it is arguable that the wetlands credit regulations intend to cover the full suite of wetland-based ecosystem services, including water quality or carbon sequestration services; these seemingly separable carbon or water quality services have already been sold when the wetland credit was sold (or applied) for mitigation. It would be a dual sale (double dipping) to enter such credits in separate markets for water quality or carbon services after having sold a wetland credit that is defined to include a comprehensive suite of services provided by the corresponding wetland acre(s).

However, credit stacking generally means providers of ecosystem service credits would be allowed to sell separate credits in separate markets for each type, even as these credits might derive from a single entrepreneurial action, likely on a single parcel of land. Through some production systems, credit production may overlap spatially for different credit types, while under other systems, production may be exclusively specialized on a single credit type. In the context of this paper, stacking policy is applied after the definition of what outputs produced will constitute creditable outcomes for corresponding environmental or ecosystem services.

The nature of ecosystem manipulation imposes this complexity on society’s effort to establish environmental markets. One result may be that credit markets will need to work with an accounting agency to track not only whether and how credits are produced, but also what criteria apply to the original certification of a credit, and whether that credit is separable from other ecosystem service dimensions for the purpose of tracking jointly produced products that may be separately sold. Our paper takes on a more limited scope. We assume what outcomes that earn certification for credits related to any particular ecosystem service are well specified; creditable actions are well defined. We assume double dipping, in the sense of dual sale or windfall profit taking, is prohibited as it would be for jointly produced private goods; that is, additionality is required. For example, a farmer can sell jointly produced beef and rawhide but can only sell each component once (legally), and the same principle applies in environmental markets. We then focus on whether well-defined credits, affecting multiple ecosystem service dimensions, jointly produced in a single, spatially delineated project, can be sold separately and stacked such that the producer receives revenue from more than one dimension of ecosystem service impacts. We investigate some of the implications of allowing stacking or disallowing stacking for efficiency achieved through environmental credit markets.

Policymakers often fail to provide a definite guideline on whether credit stacking should be allowed. 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. For policymakers, the concern is: under what conditions should an individual (or firm) producing additions to ecosystem services, through a single action or management of a single piece of land, be allowed to sell credits separately for the multiple dimensions of their complete contributions. This article strives to identify cautions about feedbacks through potential human responses to different policy incentives and influences of such responses on ecosystem outcomes.

The question of credit stacking becomes increasingly crucial as policymakers are moving to create more markets, for a variety of distinct services (e.g., Ribaudo, 2008; Stuart and Canty, 2010; Woodward and Kaiser, 2009). Both ecological and economic research is needed to resolve this question. Ecologists recognize that markets for specific services may or may not restore whole ecosystems and may alter the geographic and temporal distribution of services, with particular concern that environmental markets may not stimulate sufficient attention to ecosystem structure and function (e.g., Palmer and Filoso 2009; Raudsepp-Hearne et al. 2010, Vira and Adams 2009). The focus of ecosystem services, as benefits to humans, is a historically unfamiliar tradition for many ecologists and may stimulate substantial misunderstandings with economists. Likewise, the reliance of ecosystem services on the complexities of ecosystem structure and function is a historically unfamiliar tradition for economists and may stimulate misunderstandings with ecologists. Yet, a focus on human benefits, in conjunction with careful standards and measures for biophysical accounting can clarify conditions under which stacking is ecologically coherent, leveraging economists' insights from joint production and motives for human choice and behavior while enabling ecologists to evaluate whether environmental markets would or would not conserve ecosystem processes.

Therefore, 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.
That context differs from Horan et al. (2004) who consider efficiency factors when a credit-provider may coordinate applications for payments from multiple sources which are individually insufficient to incentivize production. We do not address the additionality problem explicitly, and we cast 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 technology or management affecting the degree of specialization in environmental credit production, and how such choices might affect environmental outcomes as well as the performance of the credit markets. It is expected that credit sellers will change their behavior 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. By behavioral responses, we refer to landowners' technological responses and change to existing plans, such as selection among alternative types of crops or a 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 follows 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, including farmers who alter management practices to provide environmental or ecological benefits. 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, we show that the framework substantially changes the conditions over which proposed policies to prohibit stacking might be in the society's best interest in a second-best world.

We hope this paper will improve the understanding and further stimulate the discussions on credit stacking. Specifically, we contribute to the literature by defining the role of specialization technology and production complementarity using a generic cost function and comparing the influence of specialization choice on the social efficiency under alternative stacking policies. Our simulation results show that the specialization choice significantly decreases the space where SM is preferred to MM in most cases, especially with a low complementarity level and a relatively flat marginal social benefit function.

2. Definition and the Analytical Framework

In this section, we first discuss the definition of credit stacking and distinguish it from the "double dipping" or "bundling" concept that is often also mentioned in the literature. We then present an analytical model that enables us to study landowners' responses given the properties of the joint production functions.

2.1. Definition of Credit Stacking

We further clarify the term credit stacking to help readers better understand the conceptual background. The credit stacking problem is sometimes framed as “double dipping” or “additionality”; these terms typically refer to the problem of whether credit sellers shall be allowed to sell multiple credit types from the same land, and definitions do differ in current literature. Here, credit stacking means “establishing [and selling] more than one credit type on spatially overlapped areas,” a definition proposed by the Electric Power Research Institute, or EPRI (Fox et al., 2011). Double dipping concerns a situation where a credit producer sells credits from a single project 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). 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 the sale of a credit. For example, double dipping occurs when sellers get payment for 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, such as selling the same credit twice.

Another dimension of the credit stacking discussion, and potentially an additional of confusion, arises from the bundling issue. Bundling or unbundling concerns how the units of different types of creditable ecosystem services are packaged for sale, either together as a single, bundled package offering multiple credit types or separated for sale in multiple markets, each addressing one ecosystem service type (Simonit and Perrings, 2013; Greenhalgh, 2008). However, bundled credits may draw together saleable units of different ecosystem services (carbon and water quality credits) in a single package for sale, *without* requiring those services to arise from a single, spatially defined project. Bundled credits do not necessarily arise from a joint production process. Raudsepp-Hearne et al. (2010) present empirical identification of ecosystem bundles using spatial data in a mixed landscape. In economics, bundling occurs when a project receives a single payment for providing multiple ecosystem services. This issue can be related to specific purposes of mitigation policies. For example, a wetland conservation credit can be defined as a bundle of underlying credits which 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 an additional return from credits for storing carbon. Theoretically, the bundling issue is not a problem as long as all the bundled credits are clearly defined, and society can accurately account for the disposition of 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 dual sale) from credits for which a producer has already been paid in full.

2.1. Difference between Choosing Credit Production Levels and the Specialization Parameter

These semantics become operationally significant because the rules of exchange in environmental markets, what is or is not allowed, will affect how markets generate change in ecosystems. The power of markets to change ecosystems, in turn, motivates regulators or environmental advocates to establish additional rules, such as an anti-stacking policy, in an effort to avoid unintended consequences, because markets can push ecosystems to human-dominated structure or set of functions producing an unnatural portfolio of ecosystem services captured in markets and other services remaining outside markets.

Given the above definitions, we note that a landowner or credit producer can choose credit production levels and the degree to which he or she will push a production system toward specialization in one ecosystem service over production of other services arising from a single site. In the forthcoming presentation, our models adopt production or cost functions that involve a single parameter to capture the level of specialization an individual can implement. When the specialization parameter is fixed, as in some prior analyses, 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 specialization parameter restricts landowners’ flexibilities to behave in substantially different ways which, if allowed, could change the shape of the iso-cost curves under different stacking policies.

The choices of the credit outputs reflect the landowners’ production decisions along the same iso-cost curve when the specialization parameter is fixed. The landowners may change the combination of carbon and water quality credits through 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. Note that the choices of credit output(s) 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, phosphorus 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 reducing the specialization level in exchange for creating more open habitat for species that do not facilitate carbon storage but do increase credits for habitat support.

Similarly, 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 requirements 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 production of water quality credits, 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 the availability of such choices to farmers could produce a biased evaluation of alternative stacking policies.

2.2.A Generic Cost Function with Production Complementarity

Woodward (2011) provides a framework that compares the SM (single-market, no-stacking allowed) and MM (multimarket, stacking allowed) in the first-best and a second-best world where the regulator ignores the production complementarity. 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. Under the multiple market policy, the landowner can sell all types of tradable credits produced from the same land. Results show that if the regulator has set the underlying caps optimally, the MM policy will achieve the socially optimal level of allocation of credit production in each dimension of environmental quality (e.g., carbon storage and water quality). However, Woodward's (2011) analysis does not fully evaluate the role of complementarity and specialization in terms of their respective influences of the marginal cost and social efficiency. To fill this gap, below we present a generic cost function to capture complementarity in producing multiple types of credits.

We assume the market prices for carbon and water quality credits are p_c and p_w. The specialization refers to a situation where the landowner has a cost advantage in producing one type of credit relative to the other, at the margin. An increase in the specialization level implies such a cost advantage increases further. 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 increase the cost to produce water quality credit at the margin. We use c and w to denote the quantity of the carbon and water quality credits, respectively. Therefore, the net social benefit function becomes

$$\max B_c(\boldsymbol{c}) + B_w(\boldsymbol{w}) - \sum_i g_i(c_i, w_i),$$

Where the total outputs of credits are summed across all producers i, so $\boldsymbol{c} = \sum_i c_i$ and $\boldsymbol{w} = \sum_i w_i$, and each producer faces iso-cost function $g_i(c_i, w_i)$, while social benefits of credits are captured in functions $B(\cdot)$For convenience, we drop subscript i when the context is clearly related to individual producer i's decision-making. We make the following two assumptions regarding the cost function.

Assumption 1. $g_{c\eta} < 0, g_{w\eta} > 0$.

Assumption 2. $g_{ww} > 0, g_{cc} > 0 \ and \ g_{cw} < 0$.

Assumption 1 defines the role of the specialization parameter η. We assume η is the specialization level for carbon credit production. An increase in the specialization level η will decrease the marginal cost of carbon and increase the marginal cost of water quality credit. In **Assumption 2**, $g_{cc} > 0$ and $g_{ww} > 0$ imply the increasing marginal cost 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 increases with the amount of carbon credit produced and decreases with the amount of water quality credit produced. The cross partial derivative g_{cw} < 0 captures the production complementarity.

Proposition 1. Given the market prices p_c and p_w, when $\frac{g_{c\eta}}{g_{w\eta}} \leq \frac{g_{cc}}{g_{cw}}$, we have $c_\eta \geq 0$ and $w_\eta >$ 0 ; when $\frac{g_{cc}}{g_{cw}} < \frac{g_{c\eta}}{g_{w\eta}} < \frac{g_{cw}}{g_{ww}}$, we have $c_\eta > 0$ and $w_\eta < 0$; when $\frac{g_{c\eta}}{g_{w\eta}} \geq \frac{g_{cw}}{g_{ww}}$, we have $c_\eta < 0$ and $w_\eta \leq 0$.

Proof. A landowner's profit

$$\pi(c, w) = p_c c + p_w w - g(\cdot)$$

is maximized when the marginal cost equals the market price for both types of credits. We use optimal supply functions that are conditional on the specialization parameter to obtain

$$\begin{cases} p_c = \dfrac{\partial g}{\partial c}(c(\eta), w(\eta), \eta) \\ p_w = \dfrac{\partial g}{\partial w}(c(\eta), w(\eta), \eta) \end{cases}.$$

Holding the credit prices constant (assuming a competitive market as in Woodward (2011)) and taking the total derivative w.r.t. η, we have

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

Solving for c_η and w_η, we obtain,

$$\begin{cases} c_\eta = \dfrac{g_{ww}g_{c\eta} - g_{w\eta}g_{cw}}{g_{cw}^2 - g_{cc}g_{ww}} \\ w_\eta = \dfrac{g_{cc}g_{w\eta} - g_{c\eta}g_{cw}}{g_{cw}^2 - g_{cc}g_{ww}} \end{cases}.$$

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,

$$g_{cc}g_{ww} - g_{cw}^2 > 0,$$

which is implicitly assumed to ensure that the profit is maximized from the first order conditions. Since $g_{cw} < 0$ due to the existence of production complementarity, the above inequality also implies

$$\frac{g_{cc}}{g_{cw}} < \frac{g_{cw}}{g_{ww}}.$$

Therefore, when

$$\frac{g_{cc}}{g_{cw}} < \frac{g_{c\eta}}{g_{w\eta}} < \frac{g_{cw}}{g_{ww}},$$

according to solutions for c_η and w_η, we can infer that $c_\eta > 0$ and $w_\eta < 0$. Similarly, when

$$\frac{g_{c\eta}}{g_{w\eta}} \geq \frac{g_{cw}}{g_{ww}},$$

we can infer that $c_\eta < 0$ and $w_\eta \leq 0$. When

$$\frac{g_{c\eta}}{g_{w\eta}} \leq \frac{g_{cc}}{g_{cw}},$$

we can infer that $c_\eta \geq 0$ and $w_\eta > 0$. *QED.*

Proposition 1 also indicates that when there is no complementarity in production, i.e., $g_{cw} = 0$,

$$\begin{cases} c_\eta = \dfrac{g_{ww} g_{c\eta}}{g_{cw}^2 - g_{cc} g_{ww}} > 0 \\ w_\eta = \dfrac{g_{cc} g_{w\eta}}{g_{cw}^2 - g_{cc} g_{ww}} < 0 \end{cases}$$

and the increase of specialization η 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 $|g_{cw}| < \left|\frac{g_{cc} g_{w\eta}}{g_{c\eta}}\right|$, $w_\eta < 0$ and when $|g_{cw}| < \left|\frac{g_{cc} g_{c\eta}}{g_{w\eta}}\right|$, $c_\eta > 0$, suggesting that a moderate complementarity level has similar marginal effects as $g_{cw} = 0$. However, an increase in the specialization toward carbon may have a negative marginal effect on the carbon credit production and a positive marginal effect on the water quality credit production when the complementarity level is high enough.

Figure 1 illustrates the major insights from **Proposition 1** regarding the role of production complementarity, identified as the origin of the credit stacking debate. In Figure 1, the horizontal axis is the quantity of carbon or water quality credit, and the vertical axis is in dollars per credit. The marginal cost curves are increasing according to **Assumption 2**: $g_{ww} > 0$; $g_{cc} > 0$. We assume an initial condition where (solid) marginal cost curves lead to equilibrium quantities *c0* and *w0* at the prices 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 1**, $g_{c\eta} < 0$, $g_{w\eta} < 0$, an increase in the specialization η 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 the new equilibrium, carbon credit c_1 is higher than c_0 and the 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 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 the production of the carbon credits will lower the marginal cost of producing 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 c_2 and w_2 may be higher or lower than the original level c_0 and w_0. The results $c_\eta > 0$ and $w_\eta < 0$ hold unless the magnitude of the complementarity level is very large, as implied by **Proposition 1**.

Note that empirical results are lacking on the magnitude of the complementarity in environmental credits production. Our research on Ohio River Water Quality Trading Project, in collaboration with EPRI, enables us to identify the associated carbon sequestration benefits (and other cobenefits such as pollinator habitat) produced from agricultural best management practices targeted primarily at water quality improvement (Liu and Swallow, 2016). Based on EPRI's projects generating water quality credits from Ohio River Watershed farms, we observe that complementarity exists in many projects producing both water quality and carbon credits. For the present analysis, we restrict attention to the interesting cases, in which an increase in the specialization parameter favoring production of carbon credits will generate an increase in relative production of c credits at the margin which cannot be reversed due to high levels of complementarity in the production of both *c* and *w* credits.[1] We will use the condition that $\frac{g_{cc}}{g_{cw}} < \frac{g_{c\eta}}{g_{w\eta}}$ as the regularity condition in our analysis, which is most likely to hold in reality even though our analysis framework suggests other, theoretically possible scenarios.

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

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

where c is the number of carbon credits and *w* is the amount of water quality credits produced by a landowner. The parameter η reflects the cost effectiveness in producing carbon credit, which is the specialization level; $\gamma = \frac{\partial^2 g}{\partial c \partial w}$ captures the production complementarity level. When $\gamma = 0$,

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[1] That is, a higher specialization level in water quality improvement should lead to an increased production of water quality credits, and similarly for carbon credits. The regularity condition assumes that the influence of complementarity on marginal cost curves cannot completely offset the influence of specialization on the marginal cost curves. The numerical version of the joint production function used in the literature (e.g., Woodward 2011) satisfies this regularity condition regarding the production cost of multiple products.

there is no complementarity and credits stacking is not an issue since there is no by-product or joint production, even if stacking is allowed.[2]

When $\gamma < 0$, production complementarity exists and the marginal cost of producing one credit might decrease in the presence of other types of credit production. In the above cost function, the specialization parameter η is restricted to $\eta \in (0,1)$. The range of η may depend on the nature (ecosystem-dependent) constraints in practice, such as the geographical locations or the crop choice due to weather limitations. A higher η denotes a more specialized technology, favoring credit type c in this example. In the case of mitigation banking, the range η 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 $g_{w\eta} = \frac{w}{(1-\eta)^2} > 0$.

Figure 2 shows the shape of the iso-cost curve 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 decreases with the specialization level.

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[2] We assume that the landowner has no control over the complementarity level, which is determined by the natural production process. Furthermore, since an increase will always lower the production cost, while the choice on the η determines the relative cost effectiveness, we focus on the landowner's flexibility of choosing a different specialization level.

Proposition 2. When the landowners can choose the specialization level, they will choose a higher specialization level in SM compared to MM under the regularity condition.

Proof. Here we define the MM as when landowners can sell, from the same project, in both c and w markets and SM as when the landowner must choose only to sell one type of credit; for this initial discussion, we assume the landowner would maximize profit by choosing to sell in the c market.[3] When the landowners can choose the specialization level, the maximization problem is

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

The first order conditions are

$$\begin{cases} p_c - \dfrac{\partial g}{\partial c} = 0 \\ p_w - \dfrac{\partial g}{\partial w} = 0. \\ \quad -\dfrac{\partial g}{\partial \eta} = 0 \end{cases}$$

Substitute the solutions $c^*, w^*, and\ \eta^*$ to the above equations, we have

$$\begin{cases} p_c - \dfrac{\partial g}{\partial c}\big(c^*(p_c,p_w), w^*(p_c,p_w), \eta^*(p_c,p_w)\big) = 0 \\ p_w - \dfrac{\partial g}{\partial w}\big(c^*(p_c,p_w), w^*(p_c,p_w), \eta^*(p_c,p_w)\big) = 0. \\ \quad \dfrac{\partial g}{\partial \eta}\big(c^*(p_c,p_w), w^*(p_c,p_w), \eta^*(p_c,p_w)\big) = 0 \end{cases}$$

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[3] Here we assume the landowners can only sell in the carbon market in the SM, which can be considered as the situation where a water quality credit market does not exist, or the incentive to participate in the water quality credit market is not strong enough. However, we do recognize when both market exist, the SM does not restrict landowners from participating in the water quality market. Our cost function specification also suggests that the landowners has a cost advantage in production carbon credit and will choose to participate in the carbon market unless the water quality credit market price is sufficiently large enough to alter the cost advantage incentive.

Take the first order condition w.r.t. p_w

$$\begin{cases} g_{cc}\dfrac{\partial c^*}{\partial p_w} + g_{cw}\dfrac{\partial w^*}{\partial p_w} + g_{c\eta}\dfrac{\partial \eta^*}{\partial p_w} = 0 \\ g_{wc}\dfrac{\partial c^*}{\partial p_w} + g_{ww}\dfrac{\partial w^*}{\partial p_w} + g_{w\eta}\dfrac{\partial \eta^*}{\partial p_w} = 1. \\ g_{\eta c}\dfrac{\partial c^*}{\partial p_w} + g_{\eta w}\dfrac{\partial w^*}{\partial p_w} + g_{\eta\eta}\dfrac{\partial \eta^*}{\partial p_w} = 0 \end{cases}$$

As a result, the partial derivative of η^* w.r.t. p_w is

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

When the regularity condition

$$\frac{g_{cc}}{g_{cw}} < \frac{g_{c\eta}}{g_{w\eta}}$$

holds, the partial derivative $\frac{\partial \eta^*}{\partial p_w} < 0$ and $\eta^*(p_w) < \eta^*(0)$ when $p_w > 0$. Therefore, the MM leads to a less specialized technology choice compared to SM where $p_w = 0$. *QED.*

Proposition 2 provides evidence that MM policy could lead to a more balanced production outcome when landowners can respond to multiple market incentives. The specialization level, such as the choice of wetland landscape or crop rotation choice, can be considered as fixed in the short term. In the long term, landowners may respond to multiple market incentives to optimize environmental benefits production, if these markets exist and are simultaneously open to jointly-produced credits. Allowing credit stacking may have a significant impact on the land use pattern or agricultural management practices.[4]

3. Numerical Simulation

In the section, we develop a simulation approach that can inform policy makers of the potential implications of landowners' responses when different market institutions are established around stacking. We assume that the two types of credits are equivalent in terms of social benefit. On the cost function choice, we still follow Helfand (1991) and Woodward (2011) and use

$$g_i = \frac{\alpha}{2}c_i^2 + \frac{1}{2\alpha}w_i^2 + \gamma c_i w_i$$

for an individual landowner i, the properties of the above function is discussed in detail in the last section. The parameter α equals $1-\eta$ from the example in Section 2 and a higher α indicates a lower specialization level. We build a simulation framework where we are able to see the influence of specialization flexibility on the relative efficiency of SM and MM policies. We still assume an additively separable benefit function with the social benefit $B(\cdot)$

$$B(\cdot) = B(\boldsymbol{c}) + B(\boldsymbol{w}) = \sum_j \left(\Omega_j \left(\sum_i j_i \right) - \frac{\theta_j}{2} \left(\sum_i j_i \right)^2 \right), j = c, w.$$

where $\Omega_j > 0, \theta_j > 0$, and the benefit function $B(\cdot)$ is assumed to be the same for carbon and water quality credits. Based on the benefit and cost functions, the "optimal" cap be found at (Woodward, 2011):

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[4] Note that one implicit assumption is that we assume interior solutions always exist in Propositions 1 and 2. While the necessary and sufficient conditions have been discussed in Woodward (2011), it is straightforward from Figure 2, where the price ratio will determine the optimal production on an iso-cost curve. The interior solutions will always exist due to the production complementarity and we can always find a point where the marginal cost of producing one type of credit is zero.

$$\hat{A}^{*} = \frac{\Omega(2\gamma\alpha - \alpha^2 - 1\,)}{(\gamma^2\alpha + 2\gamma\theta\alpha - \alpha^2\theta - \alpha - \theta)},$$

where α is the initial specialization level.[5] Also, the net benefits in these two market institutions can be expressed as

$$NB^{MM}(\hat{A}\,) \\ = \frac{-\hat{A}\big(\hat{A}\alpha^{MM}\gamma^2 + 2\theta\hat{A}\gamma\alpha^{MM} - 4\Omega\gamma\alpha^{MM} + 2(\alpha^{MM})^2\Omega - \theta\hat{A}(\alpha^{MM})^2 - \hat{A}\alpha^{MM} + 2\Omega - \theta\hat{A}\big)}{(2\gamma\alpha^{MM} - 1 - \alpha^{MM})}$$

and

$$NB^{SM}(\hat{A}\,) = -\Big(2\Omega(-1 + \gamma\alpha^{SM}) + \theta\hat{A}(1 - 2\gamma\alpha^{SM} + (\alpha^{SM})^2\gamma^2) + \hat{A}\alpha^{SM}(1 - \gamma^2)\Big)\,\hat{A}.$$

Different from Woodward (2011) where the specialization level is fixed in MM and SM, we recognize that landowners may choose a different specialization level in these two market institutions. The specialization levels α^{MM} and α^{SM} represent the optimized specialization choice when the landowners' have the flexibility to change under certain constraints. **Proposition 2** shows that landowners will choose a less specialized technology in SM for a generic cost function specification.

According to the benefit function, there exists an A^c where the two market institutions yield equivalent net benefits and if the chosen cap $\hat{A} > A^c$, MM will perform better in terms of social net benefit and *vice versa*.[6] The value of $\hat{A}$ can be found from $NB^{SM}(\hat{A}\,) = NB^{MM}(\hat{A}\,)$. To

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[5] One can also derive an optimal cap that incorporates the landowners' choice on the specialization level. However, a social planner may not consider the landowners' responses or not have information on the flexibility of landowners' choices. More importantly, since our major goal is to compare the influence of specialization choice with the baseline when the specialization level is fixed, using the same cap choice allows us to compare different alternatives on a common ground. We suggest this assumption corresponds well with the primary debate around credit stacking polciy, wherein most advocates have assumed the production technology is a fixed aspect of nature.

[6] Woodward shows that the ratio of $NB^{SM}(\hat{A}\,)/NB^{MM}(\hat{A}\,)$ decreases as the cap $\hat{A}$ increases and based on the boundary conditions, a unique cap A^c approaches where the specialization α is the same in the SM and MM.

proceed, we graph the contour curves of $A^c/\hat{A}^*$ over a range of the specialization level α and the complementarity level γ. To be comparable to Woodward (2011), we also choose two values of the marginal benefit parameter, $\theta = 0.5$ and $\theta = 2$. In addition, we assume four different levels of flexibility (5%,10%, 20%, and 30% change from the initial level) on the specialization choice, along with a baseline level when the specialization is fixed. Simulation results are presented in Figure 3, where the solid curves represent the baseline with fixed specialization level, the same as the left panel in Woodward's (2011) Figure 5. The dotted lines in Figure 3 show the alternative scenarios when landowners can choose a different specialization level in response to the incentives created by SM or MM institutions. The horizontal axis is the initial specialization level, and the vertical axis is the complementarity level. Each contour curve divides the space into two regions. The left-lower region represents the parameter combinations where the SM performs better when the cap is set within at least X% of the optimal cap $\hat{A}^*$, where the X is the ratio shown on the contour curves. For example, the curve with a numerical value 0.9 means that SM performs better than MM in the region to the left of the curve and MM performs better in the region to the right of the curve when the cap is set to equal at least 90% of the optimal level.

We first look at the case $\theta = 0.5$ where the marginal benefit function is relatively flat. Figure 3a, 3b, 3c, and 3d show the results when the range of flexibility is within 5%, 10%, 20%, and 30% of the initial specialization level, respectively. The specialization level is chosen at the optimal level within range based on the functional form specified, and the optimal specialization levels are different in SM and MM. We find that allowing the flexibility to choose the specialization

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Following the same procedure, one can demonstrate this result still holds when the specialization α is different in SM and MM.

level significantly shrinks the region where SM is preferred to MM in terms of net social benefit, *except* at a very high complementarity level (in our simulation, around -0.8 or -0.9). When the range of flexibility increases, the choice on the specialization level further shrinks the region where the SM is preferred. According to our simulation and parameter choices, it is almost always the case that the specialization choice shrinks the region where the SM is preferred when $\gamma > -0.8$. Therefore, when the marginal benefit function is reatively flat, the flexibility to choose the speciation level *further* increase the relative advantage of MM compared to SM over a large set of parameter values.

When $\theta = 2$ and the marginal benefit function is relatively steep, Figure 4a, 4b, 4c, and 4d show the results when the range of flexibility is within 5%, 10%, 20%, and 30% of the initial specialization level, respectively. The solid curves are when there is no flexibility in the specialization choice, the same as the Figure 5 (right panel) in Woodward (2011). We find that allowing the flexibility to choose the specialization level significantly shrinks the region where SM is preferred to MM in terms of net social benefit when the complementarity level $\gamma > -0.5$. When the range of flexibility increases, the choice on the specialization level further shrinks the region where the SM is preferred for when the complementarity level is small. However, it also increases the region where the SM is preferred when the complementarity level is large.

In this section, we demonstrated numerically that when the cap is not set at the optimal level and when the SM outperforms MM, after consideration of landowners' potential responses, the region where SM is preferred to MM shrinks in most cases, especially when the complementarity level is small, and the marginal benefit curve is flat (very low marginal benefit change). Though we lack the empirical estimations on the complementarity level in the production of various types of environmental benefit, as mentioned before, our experience with the Ohio River Water Quality Trading Market does suggest that the complementarity is unlikely to alter the direction of marginal cost curve shift when the specialization level changes.

4. Discussion and Conclusion

In this paper, we provide an analytical framework to study landowners' responses toward a policy implementing or prohibiting credit stacking, focusing on landowner's specialization choices. 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, and when credit stacking is not allowed, landowners tend to choose a more specialized production technology. As a result, the multiple market institution leads to a more balanced production approach from the market participants. We also replicate Woodward's simulation results and compare them with the outcomes when the responses are considered. We find, after considering landowners' responses, the region where SM is preferred to MM significant shrinks in most cases. However, the simulation also points out, for the unlikely scenarios with high complementary in production technology, our result may reverse: the MM institution may lead to a more specialized production (when the regularity condition is violated), and the region where SM is preferred to MM will expand.

Woodward's (2011) contribution remains, to date, as the single formal analysis of economic implications of credit stacking in the context we raise here. Paraphrasing, his main conclusion was that anti-stacking policy could improve social welfare outcomes (efficiency), but only when the regulator sets caps for regulatory-based (cap-and-trade) environmental credits that depart from the socially optimal caps The intuition behind his result traces to the general implications of second best theory (Lancaster and Lipsey, 1959; Davis and Whinston 1965): if the economic system includes constraints that violate the conditions of perfect competition – i.e., extra constraints that lead to a second-best set of conditions – then policy makers may need to use unconventional (from an economist's perspective) tools to assist markets to achieve marginal conditions consistent with efficiency, a role played by the SM policy. Our results, connected directly with Woodward's (2011) seminal model for credit stacking, built on Helfand's (1991) earlier work, indicates that the possibility of producer response to incentives created by the SM policy makes the potential gains from SM applicable under a much more restrictive range of illustrative conditions. Unfortunately, while new and intriguing, the nature of second-best theory demands empirical investigations to derive definitive policy conclusions. Thus, our analysis raises a valid caution against policies that would prohibit credit stacking, but only empirical work can provide more definitive guidance for how these conditions might apply to a particular set of credit markets.

We present an analytical framework that advances the stylized analysis where landowners' 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 counterproductive consequences is that policymakers often ignore agents' choice and flexibility which would often offset the incentive which a policy intends to introduce to discourage a less desirable outcome. Our results imply that the SM restriction is likely to magnify the inefficiency compared to the MM in the long run, especially with a small or moderate complementarity level. We also 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.

Our analyses are based on the premises where the markets exist to trade jointly produced environmental credits. In reality, we realize the difficulty of establishing and sustaining environmental markets. However, we also expect that opening the possibility of credit stacking will provide a stronger incentive for suppliers to participate in the environmental market and benefit from a diversified revenue stream. Our current research complements existing research on designing new payment mechanisms to encourage private payment for public goods such as the environmental/ecological benefits (Liu et al., 2016; Liu and Swallow, *forthcoming*; Swallow et al., 2018) and an environmental market can only be successful when both supply and demand sides are provided with sufficient incentives to participate in the market. Farmers can become a substantial supplier of the market by altering their management practices and opening the possibility of credit stacking would further benefit farmers and other environmental benefit suppliers, though numerous challenges are ahead for this to become a reality.

It is also important to consider additional benefits from a more balanced production approach, such as the biodiversity enhancement value. Biodiversity is an important criterion 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 is highly aligned (Polasky et al., 2012; Ricardo 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, the landowner may acquire extra revenue from a balanced production (Bull et al., 2013).

We use carbon and water quality credits as examples to illustrate the credit stacking problem throughout the paper. The carbon emission has a global impact, thus, to address the externality the 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 geographically more 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. These questions are of interest to future research.

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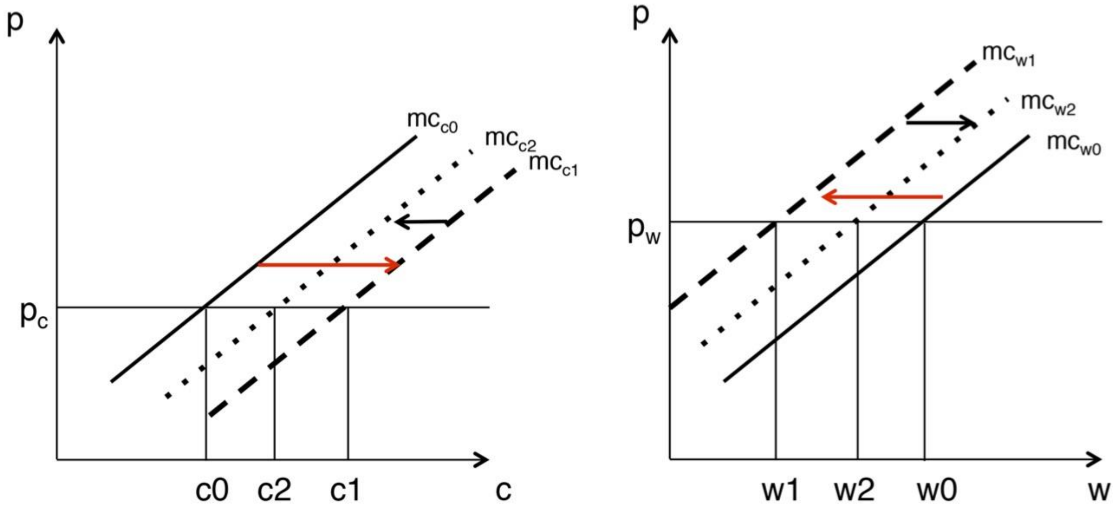
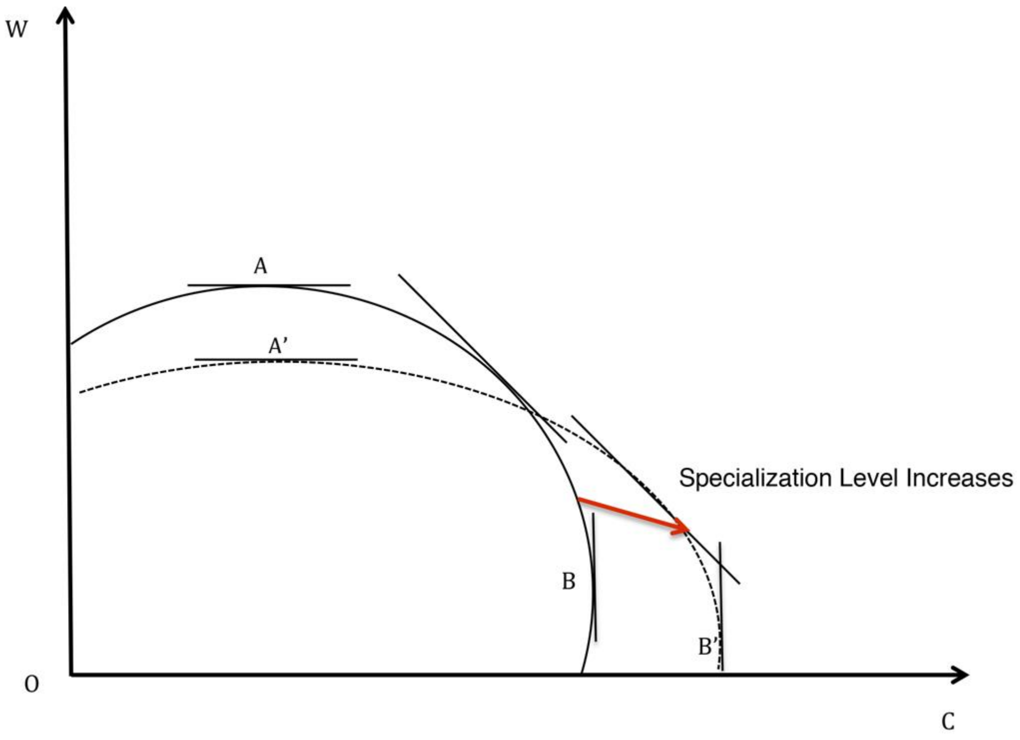
Figure 1: The Influence of Production Complementarity.



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 in dollars per credit. The marginal cost are curves are increasing for both types of credits. We use the increase of specialization level for carbon credit production as an example. 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. The existence of higher level of production complementarity restrict that shift to marginal cost curves mc_{c1} and mc_{w1} in the equilibrium. Under the regularity condition, mc_{c2} is still to the right of mc_{c0} and mc_{w2} is still to the left of mc_{c0}. However, a very large complementarity level may offset and even reverse the impact of the specialization level. As a result, mc_{c2} is may be shifted to the left of mc_{c0} and mc_{w2} may be shifted to right of mc_{c0} when specialization level changes.

Figure 2: The Cost Curve and the Change of the Specialization Level.



Note: This Figure illustrates a generic cost function that satisfies our assumptions. The horizontal axis and vertical axis are the amount of carbon credit and water quality credits 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. The two iso-cost curves differ in the specialization level and an increase of specialization changes the curve from AB to A'B'. 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 for carbon production.

Figure 3. The Influence of Specialization Choice on the Comparison of SM and MM Institutions, Flat Marginal Benefit Curve.

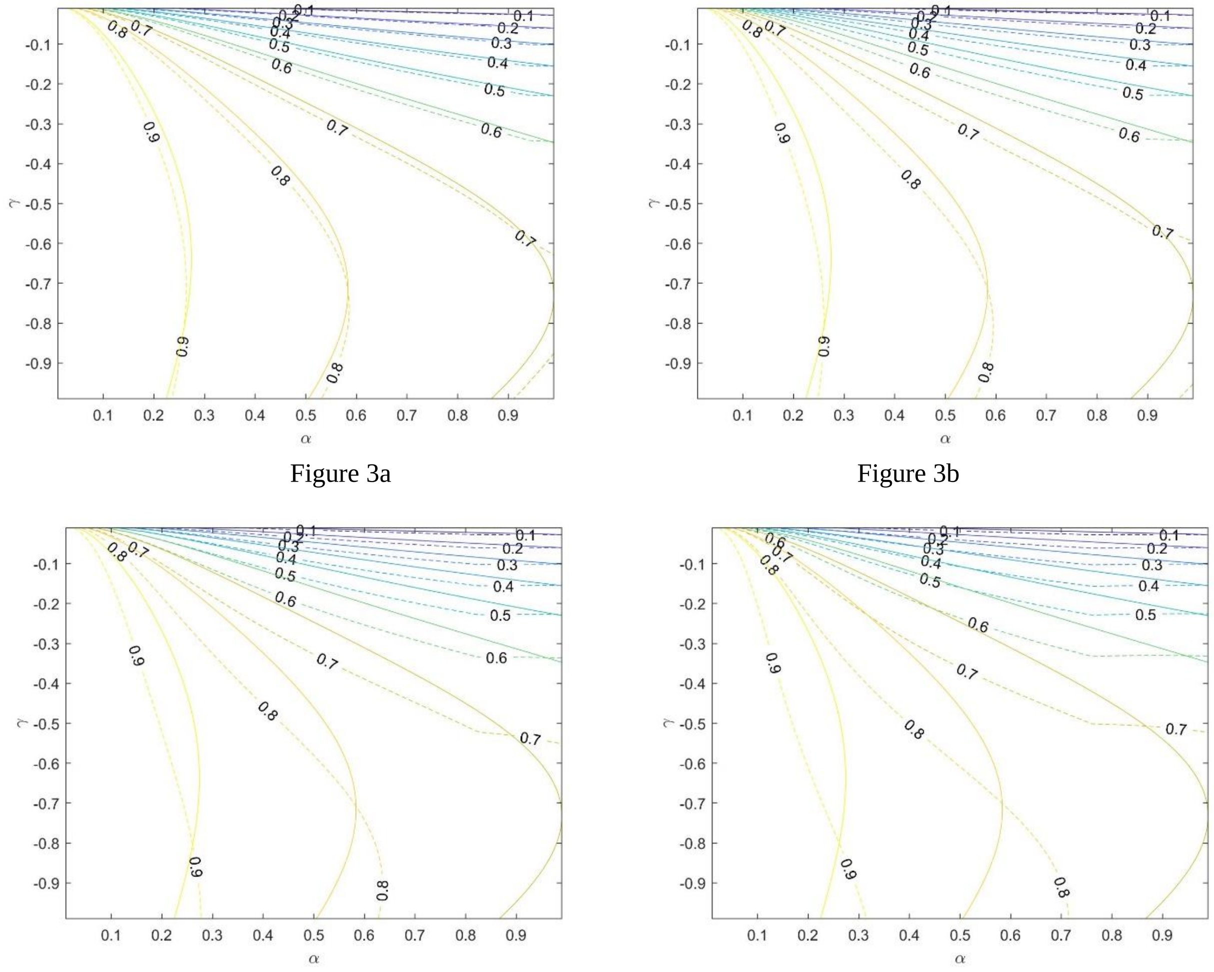


Figure 3a

Figure 3b

Figure 3c

Figure 3d

Note: Figure 3a, 3b, 3c, and 3d show the situation where the range of flexibility is within 5%, 10%, 20%, and 30% of the initial specialization level, respectively. The specialization level (α) is chosen at the optimal level within range based on the functional form specification and the optimal specialization levels that differ under SM and MM policies. The vertical line is the complementarity level, γ. The solid curves assume no flexibility in choosing the specialization level while the dotted curves in each figure assume a certain degree of flexibility in the specialization choice. The curve with a numerical value X means that SM performs better than MM in the region to the left of the curve and MM performs better in the region to the right of the curve when the cap is set to equal at least X of the optimal level. We also assume a relatively flat marginal benefit curve ($\theta = 0.5$) in the figure.

Figure 4. The Influence of Specialization Choice on the Comparison of SM and MM Institutions, Steep Marginal Benefit Curve.

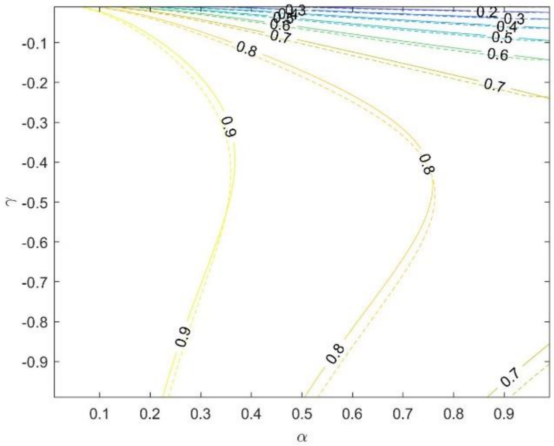


Figure 4a

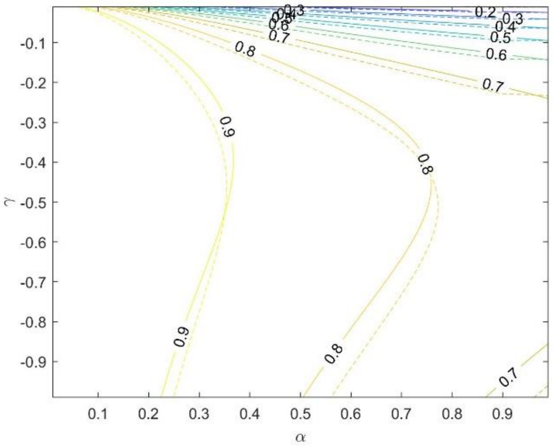


Figure 4b

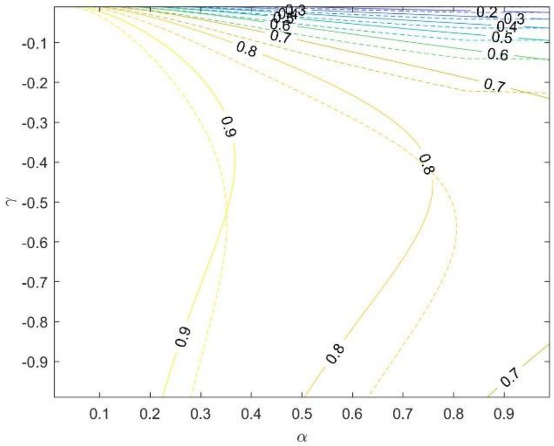


Figure 4c

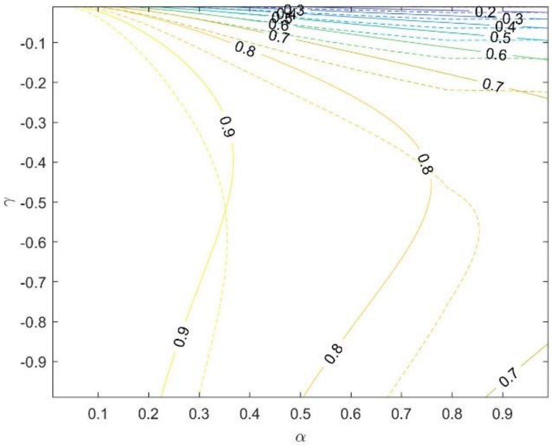


Figure 4b

Note: Figure 4a, 4b, 4c, and 4d show the situation where the range of flexibility is within 5%, 10%, 20%, and 30% of the initial specialization level, respectively. The specialization level (α) is chosen at the optimal level within range based on the function form specification and the optimal specialization levels are different in SM and MM. The vertical line is the complementarity level, γ. The solid curves assume no flexibility in choosing the specialization level while the dotted curves in each figure assume a certain degree of flexibility in the specialization choice. The curve with a numerical value X means that SM performs better than MM in the region to the left of the curve and MM performs better in the region to the right of the curve when the cap is set to equal at least X of the optimal level. We also assume a relative steep marginal benefit curve $(\theta = 2)$ in the figure.